GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[x] ORIGINAL [ ] REVISION NO. ____

Project No. E-24-654 (E-24-354 c/s) DATE 4/16/82

Project Director: Dr. Michael E. Thomas School/Lab ISyE

Sponsor: NSF

Type Agreement: Grant No. MEA-8201530

Award Period: From 4/15/82 To 3/31/83 (Performance) 6/30/83 (Reports)

Sponsor Amount: $18,989 Contracted through:

Cost Sharing: $198 GTRI/~~GIT~~

Title: A Workshop on Research Directions in Industrial Engineering

ADMINISTRATIVE DATA

OCA Contact Linda H. Bowman x4820

1) Sponsor Technical Contact:

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NSF
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202-357-7540

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202-357-9626

Defense Priority Rating: ____ Security Classification: ____

RESTRICTIONS

See Attached NSF Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with GIT

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GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION SHEET

8R205-2

Date 11-10-82

Project Title: A Workshop on Research Directions in Industrial Engineering

Project No: E-24-654

Project Director: M. E. Thomas

Sponsor: NSF

Effective Termination Date: 3/31/83

Clearance of Accounting Charges: 6/30/83

Grant/Contract Closeout Actions Remaining:

- [x] Final Invoice and Closing Documents
- [ ] Final Fiscal Report
- [x] Final Report of Inventions
- [x] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
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FINAL REPORT

A WORKSHOP ON RESEARCH DIRECTIONS IN INDUSTRIAL ENGINEERING

By

Michael E. Thomas, Principal Investigator

Under

NSF Grant No. MEA–8201530

Report Period Covered April 15, 1982 to March 31, 1983

GEORGIA INSTITUTE OF TECHNOLOGY

A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA

SCHOOL OF INDUSTRIAL & SYSTEMS ENGINEERING

ATLANTA, GEORGIA 30332

A WORKSHOP ON RESEARCH DIRECTIONS IN INDUSTRIAL ENGINEERING

Michael E. Thomas
Principal Investigator
NSF Grant No. MEA-8201530

Final Project Report Covering the Period
April 15, 1982 to March 31, 1983

NATIONAL SCIENCE FOUNDATION
Washington, D.C. 20550

FINAL PROJECT REPORT
NSF FORM 98A

PLEASE READ INSTRUCTIONS ON REVERSE BEFORE COMPLETING

PART I–PROJECT IDENTIFICATION INFORMATION

1. Institution and Address	2. NSF Program	3. NSF Award Number
Georgia Institute of Technology Atlanta, Georgia 30332	Electrical, Computer & Systems Engineering	MEA - 8201530
	4. Award Period From 4/15/82 To 3/31/83	5. Cumulative Award Amount $18,989

6. Project Title

A Workshop on Research Directions in Industrial Engineering

PART II–SUMMARY OF COMPLETED PROJECT *(FOR PUBLIC USE)*

A workshop to define research directions in Industrial Engineering for the next decade was held in Atlanta in early May. A cross section of Industrial Engineers from industry, government and academia participated. So much discussion resulted that a follow-on was held in New Orleans at the IIE annual spring meeting. A set of research objectives was identified and prioritized. In addition, a useful dialogue was established between the research community, the users, and the various funding agencies.

PART III–TECHNICAL INFORMATION *(FOR PROGRAM MANAGEMENT USES)*

1. ITEM *(Check appropriate blocks)*	NONE	ATTACHED	PREVIOUSLY FURNISHED	TO BE FURNISHED SEPARATELY TO PROGRAM Check (√)	Approx. Date
a. Abstracts of Theses					
b. Publication Citations					
c. Data on Scientific Collaborators					
d. Information on Inventions					
e. Technical Description of Project and Results					
f. Other *(specify)*					

2. Principal Investigator/Project Director Name *(Typed)*	3. Principal Investigator/Project Director Signature	4. Date
Michael E. Thomas		10/8/82

FINAL REPORT

Introduction

The American Institute of Industrial Engineers formed a Task Force to interact with the National Science Foundation in an attempt to enhance the recognition that Industrial Engineering receives from the Foundation. This task force consisted of Dr. Ken Case, Chairman; Dr. Al Bishop, Dr. Bill Biles, Dr. Al Holtzman and Dr. Mike Thomas. This group met initially in Detroit at the 1980 annual conference of the Institute and developed a plan of action. One activity was to approach the engineering leadership at the Foundation. Drs. Case, Bishop and Thomas thus arranged a meeting with Dr. Henry Bourne, then the Deputy Assistant Director of the Engineering Directorate, and Dr. Alvin Strauss, Division Director of the Mechanical Engineering and Mechanics Division. At that meeting we were encouraged to hold a workshop to define research directions in Industrial Engineering. This was viewed as a first step both to focus our research objectives and also to acquaint NSF with Industrial Engineering. As a result of this encouragement the Task Force asked Dr. Thomas to prepare a proposal for a workshop to be held in Atlanta at Institute Headquarters. Extensive interaction occurred between Dr. William Spurgeon of NSF and Dr. Thomas during the planning for the workshop. A proposal was prepared and a list of participants developed to include industrial and governmental representatives. The proposal was funded and the workshop was held May 2, 3 and 4, 1982. Because time was so limited a follow-on effort was conducted at the IIE annual spring meeting in New Orleans on Monday, May 24, 1982. Efforts were made to develop a set of high priority items to be recommended to NSF for assistance in directing their limited resources. A summary of that meeting is given later in this report.

It should be noted that the participants in the workshop felt uniformly that the efforts involved were worthwhile. The industrial participants were very outspoken and supportive of the goal to orient the Foundation's research program to help understand and solve many of the serious problems effecting U.S. industry as they design and operate much more highly integrated and automated manufacturing systems. The considerable interchange at this workshop was extremely useful. It was also pointed out that many industrial colleagues are becoming more concerned about the questions affecting engineering education and are willing to provide financial and personnel support to help alleviate some of the serious problems. This support will not only be directed at the teaching programs but at research activities as well. In the Industrial Engineering area the Computer Integrated Manufacturing program at Purdue University, the Materials Handling Research Center at Georgia Tech and the Robotics Center at Rhode Island University are some notable examples. The latter two were in fact established with NSF seed money support.

In summary, the workshop achieved the objectives of the organizers. Meaningful dialogue was established between NSF and members of the IE research community. Research objectives were priortized, with some caveats - of which NSF is fully cognizant. Finally, the leadership of the IE community indicated a meaningful commitment to support research as an objective of the profession.

Description of Participants

The participants were selected to represent four constituencies which were not mutually exclusive. An attempt was made to include members of the academic, industrial, and governmental communities as well as the leadership of the Institute of Industrial Engineers. Three of the industrial invitees had to cancel at the last minute due to pressing business considerations. Efforts were made to attract some of the leading individuals from the research community. For example, two of the invitees were recipients of the David Baker Distinguished Research Award of the Institute. The industrial invitees were top industrial engineering managers. The IIE leadership was represented by Dr. Joe Mize, Past President, current President Barry Mundt, and Dr. John White, President-Elect. A complete list of those invited is shown below:

1. Dr. Joseph Mize, Past President IIE
   School of Industrial Engineering and Management
   Oklahoma State University
   Stillwater, OK 74078

2. Mr. Barry Mundt
President IIE
Principal-Peat, Marwick and Mitchell
2100 Peachtree Center South
Atlanta, GA 30303

3. Dr. John White, Director
Materials Handling Research Center
and President-Elect IIE
School of Industrial and Systems Engineering
Georgia Institute of Technology
Atlanta, GA 30332

4. Dr. David Belden
Executive Director, IIE
25 Technology Park/Atlanta
Norcross, GA 30092

5. Mr. Jim Wolbrink
Managing Director
Education and Publications, IIE
25 Technology Park/Atlanta
Norcross, GA 30092

6. Dr. Tom Baker, Staff Advisor
Communications and Computer Sciences Department
Exxon Corporation
P.O. Box 153
Florham Park, NJ 07953

7. Mr. Mike Cubbin, Director
Industrial Engineering
Fisher Body Division
General Motors Corp.
Warren, MI 48090

8. Dr. Jim Bontadelli, Manager
Industrial Engineering
Tennessee Valley Authority
100 Hamilton Bank Annex
Knoxville, Tennessee 37902

9. Mr. Orlando J. (Lanny) Feorene
Director, Management Services Division
Kodak Park Division
Eastman Kodak Company
1669 Lake Avenue
Rochester, New York 14650

10. Mr. Harry Heist, Manager
Industrial Engineering Applications
General Electric Corporation
Building 36, Room 107
1 River Road
Schenectady, New York 12345

11. Dr. David M. Miller
Corporation Coordinator
Productivity Analysis
Ethyl Corporation
330 South Fourth Street
P.O. Box 2189
Richmond, VA 32317

12. Mr. Philip S. Moore, Jr.
Manager, Industrial Engineering
The Proctor & Gamble Co.
7162 Reading Road
Cincinnati, OH 45222

13. Dr. Stan Settles, Manager
Industrial Engineering
Garrett Corporation
Pneumatics Systems Division
P.O. Box 5217
Phoenix, Arizona 85010

14. Dr. Abraham H. Haddad
Program Director
Systems Theory and Operations Research
Division of ECSE
Directorate for Engineering
National Science Foundation
Washington, D.C. 20550

15. Dr. William Spurgeon, Director
Production Research Program
Directorate for Engineering
National Science Foundation
Washington, D.C. 20550

16. Dr. Thomas Varley
Office of Naval Research
Department of the Navy
800 North Quincy Street
Arlington, VA 22217

17. Dr. Al Bishop
Department of Industrial and Systems Engineering
Ohio State University
Columbus, Ohio 43210

18. Dr. Ken Case
Department of Industrial and Management Engineering
Oklahoma State University
Stillwater, Oklahoma 74078

19. Dr. Ralph Disney
Department of Industrial Engineering
and Operations Research
302 Whittemore Hall
Virginia Polytechnic Institute and
State University
Blacksburg, Virginia 24061

20. Dr. Richard Francis
303 Weil Hall
Department of Industrial and Systems Engineering
University of Florida
Gainesville, Florida 32611

21. Dr. John Ramberg
Department of Systems and Industrial Engineering
University of Arizona
Tucson, Arizona 85721

22. Dr. Donald Ratliff
School of Industrial and Systems Engineering
Georgia Institute of Technology
Atlanta, GA 30332

23. Dr. William Rouse
School of Industrial and Systems Engineering
Georgia Institute of Technology
Atlanta, GA 30332

24. Dr. Jim Solberg
Department of Industrial Engineering
Purdue University
West Lafayette, Indiana 47907

25. Dr. Michael E. Thomas, Director
School of Industrial and Systems Engineering
Georgia Institute of Technology
Atlanta, GA 30332

Mr. Moore, Mr. Heist, and Dr. Settles were unable to attend.

Discussion of Position Papers Presented

In this section we will attempt to summarize the position papers which were presented at the workshop. The papers which were presented are listed below and are presented in full in the Appendix. Several intriguing ideas are presented and the reader is urged to read through the full texts.

The first paper presented was written with the goal of defining the science base of industrial engineering. The paper entitled

"Industrial Engineering Science Base"

was written by Dr. Joseph Mize and Dr. Kenneth Case, and uses an excellent approach to outlining the fundamental principles underlying Industrial Engineering.

The remaining papers were an effort to focus on important research issues confronting Industrial Engineering. First was a paper by Dr. William Rouse, Director of the Man-Machine Systems Research Center, Georgia Institute of Technology. His paper was entitled

"Human Interaction with Complex Systems: A Research Prospectus."

The second was written by Dr. Al Bishop of the Ohio State University. The title of his presentation was

"The Industrial Engineer's Role in Manufacturing Systems Research."

Dr. James Solberg, a member of the Computer Integrated Manufacturing Program at Purdue University presented his ideas in a paper entitled

"Opportunities for IE Research in Manufacturing."

Finally, Dr. Donald Ratliff, Director of the Center for Production and Distribution Research at Georgia Tech, presented his views in

"Research Focus in Production and Distribution Research."

After reading these papers and listening to the discussions which occurred at the workshop it appears that research problems fall into two main areas. The first involves questions of how to best design complex productive systems and the second involves how to operate these complex systems well. There seemed to be general agreement that such questions are exceedingly difficult. In the former case, for example, the problems are often poorly defined and have multiple objectives. In facility design we have an extensive literature but little of it has made an impact and does not offer hope for additional major breakthroughs so that a design methodology can be evolved. In the latter case the area of scheduling offers another example of where a vast literature is available but offers little help in solving many of the existing large scale problems.

Another operational problem of concern is how to handle the inevitable changes that arise and which must be accomodated on-line. For example, when a long range production schedule is developed it is based on certain demand assumptions. As time evolves we obtain better information regarding the demand which requires changes in the production schedule. How to handle such rescheduling is an important but unresolved issue. Another example is in the "group technology" area. Much has been written about benefits which will occur but little hard evidence is available which would lead to development of other than a seat-of-the-pants design. Flexible manufacturing systems also appear to offer benefits but no research results are available to help reconfigure such systems.

In each paper and in the discussions it became clear among those present that two approaches were necessasry. The first was that researchers needed to have more empirical knowledge and experience with the problems associated with design and operational control in order to formulate more realistic approaches. The second concensus which evolved was that the avenues which offered the best opportunities for final solution approaches to solve these complex problems was an interactive approach. This involves the problem solver and a "friendly" computer interface working together. Questions of what to model for computer solution and what to reserve for the human problem solver are examples of the interesting research questions which arose at the workshop. These observations were consistant with the list of research priorities which evolved at the continuation in New Orleans. These recommendations are listed below.

Research Priorities

As a result of time limitations at the workshop it was decided to continue the discussions at the Spring Meeting of the Institute. The goal for the continuation was to attempt to define certain priorities for research.

Only four hours were allotted for this NSF/IE Research Workshop Continuation. The task of indentifying and prioritizing Industrial Engienering research topics is, as with other widely diversified engineering disciplines, extremely difficult if not impossible. In any event, a decision was made to utilize this time in such a way that topics would be identified and prioritized, even though the input and prioritization would be imperfect.

In order to accomplsih the objective, Dr. D. Scott Sink of Oklahoma State University was invited to attend and facilitate the collection, summarization, and prioritization of input using the Nominal Group Technique upon which he is a recognized expert. Also in attendance was Dr. George L. Smith, Jr. of Ohio University who is another expert on an NGT procedures. The four basic activities included the following:

(1) Silent generation of research direction, problem areas, and/-or needs (invitees were requestesd to come prepared with this type of input, but the silent generation technique gave them each an opportunity to either develop or crystallize their input to the next process).

(2) Round robin input from each attendee in which only one research item is presented. At this time the group is not allowed to criticize or discuss in detail any inputs. This process continues around the group until no participant has any additional input. This portion of the process is very effective in obtaining input from all individuals, including those who are normally very quiet in a group process. It also tends to limit those who dominate a group process.

(3) Clarification and consolidation of listed items. Items which are felt to be duplicates of others or items which are not understood are briefly discussed. Consolidation of topics may take place by eliminating one topic and including it as a subtopic of another item.

(4) Individual selection of the eight most important (or highest priority) topics from the generated list, followed by prioritization such that the highest priority topic obtains an individual score of eight (8) and the eighth priority topic receives a score of one (1). This procedure consumed something over three hours and results were obtained.

Attendees were given the following instructions regarding their inputs to the research topic list. (1) Identify reseach direction, problem areas, and/or needs, (2) include specific research problems, tasks, and/or questions within each major area of item (1) and, (3) think in terms of a five (5) to ten (10) year research horizon.

The prioritization process resulted in the following 9 items having the largest number of people voting, as well as the largest overall voting score per item.

(1) Human/Computer interface

(2) Management of quality

(3) Conceptual framework for CAD, CAM, CAT, and CAD/CAM/CAT

(4) Computer-aided management decision support systems

(5) Design process improvement

(6) Large scale systems design and operation

(7) Interactive scheduling (quick fix)

(8) Office automation and white collar productivity

(9) Interactive design.

In summary the workshop appeared to achieve its objectives. An amazing degree of concensus on research priorities occurred in view of the breadth of the Industrial Engineering profession. It is hopeful that this information will prove useful to NSF (and other) program managers in guiding their research.

INDUSTRIAL ENGINEERING SCIENCE BASE

Position Paper

NATIONAL SCIENCE FOUNDATION WORKSHOP

on

INDUSTRIAL ENGINEERING

May 3-4, 1982

IIE Headquarters
25 Technology Park/Atlanta
Norcross, Georgia

Prepared by:

Joe H. Mize
Kenneth E. Case
Oklahoma State University

EXECUTIVE SUMMARY

The authors were asked to prepare a position paper defining the science base of industrial engineering. The purpose of this and other invited position papers is to develop an understanding among IE researchers in academia and professional practice on the one hand, and officials of the Engineering Directorate within the National Science Foundation on the other, about the fundamental principles (the science base) upon which IE tools are based.

In attempting to define the science base underlying industrial engineering, the authors took a generic approach. An effort was first made to define and classify IE functions (what IE's do in the world of work). Having done that, the next step was to identify those tools, techniques, and methodologies used by IE's in performing their functions. Finally, the pertinent areas of basic and applied science were carefully surveyed to identify fundamental concepts, principles, laws, and knowledge which provide a collective foundation upon which IE tools are based.

Any attempt to define the science base of a discipline as diverse as industrial engineering is presumptuous at best. Indeed, this report contains many presumptions on the part of the authors. It should be viewed as a point of departure and not a definitive statement.

INDUSTRIAL ENGINEERING SCIENCE BASE

I. INTRODUCTION

The development of industrial engineering as a formal academic discipline and as a field of professional practice has been evolutionary, occurring over a long period of time. Concepts relating to efficient work methods, worker motivation, etc., can be found in biblical writings.

In general, industrial engineering emerged as a result of the need for individuals having a unique skill combination: technological know-how and "people-skills." The industrial revolution resulted in large systems of production whose many diverse functions and components had to be carefully planned, coordinated and managed. A typical large manufacturer would have thousands of machines, perhaps a dozen plant sites, tens of thousands of workers--all operating simultaneously to meet production goals in the most efficient and effective manner possible.

Figure 1 is included to portray a general chronology of key developments and events which were fundamental to the development of IE (dates are approximate). The practice of IE began with an emphasis on the micro-analysis of individual workers and individual work places, primarily in manufacturing operations. It evolved to include a broader view of production processes. Today and in the future, IE's are expected to design optimal total productive work systems for all types of organizations.

The role of the IE in the world of work changes in response to three primary driving variables:

Technological Developments - Processes, equipment, automation, controls,

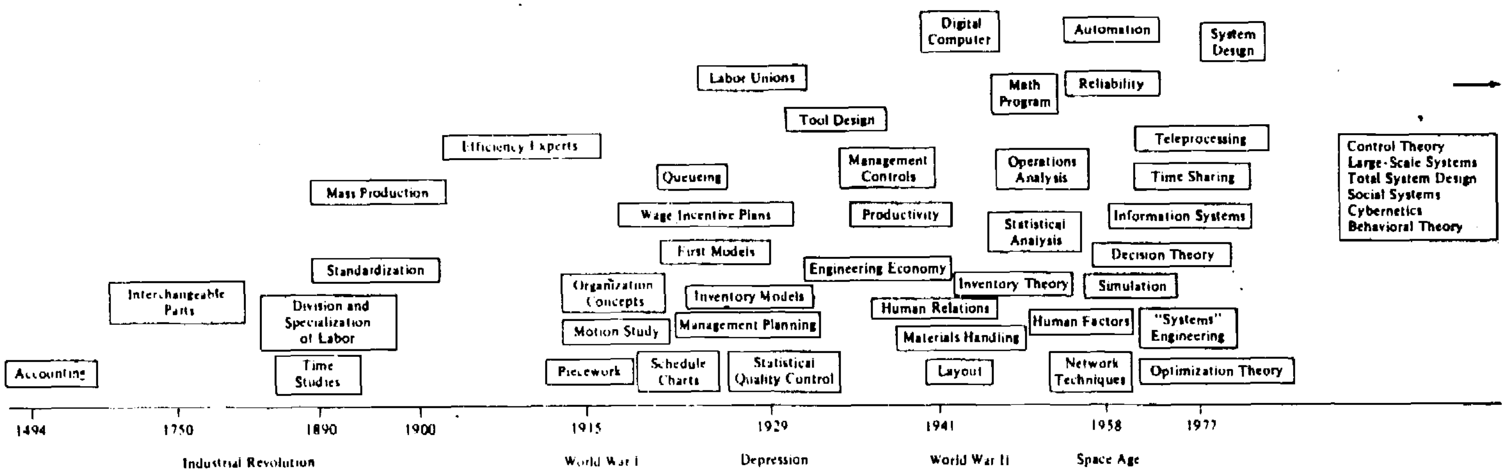

Figure 1. A chronology of significant events and developments in the evolution of industrial engineering. (From Turner, Mize, and Case, Introduction to Industrial and Systems Engineering. Prentice-Hall, 1978)

information systems, etc.

Sociological Developments - Education and skill level of work force, expectations of workers, worker response to incentives, desire for participation in decision making, government regulations, evolving sociological values and practices, etc.

IE Science Base and Tools - Accumulated knowledge base concerning human performance, operational systems; adaptation of principles, laws, techniques from other disciplines; tools, techniques, methodologies for performing IE functions.

A fourth variable driving the IE role must also be recognized; the organization representing the collective interests of the IE profession, the Institute of Industrial Engineers. IIE will be an increasingly significant force in influencing and directing the development of IE methodology and the underlying IE science base.

It is clear that Industrial Engineering plays a critical role in the world of work in any industrialized society. In recent years, IE's have begun practicing in many new types of organizations: banks, hospitals, city governments, insurance companies, transportation firms, regulatory agencies, etc. The demand for IE's greatly exceeds the available supply. This demand/supply imbalance is greater for IE than for any other engineering or science field and is projected to exist for many years in the future.* The relative projections of supply and demand for the major engineering disciplines are shown below:

---

*Science and Engineering Education for the 1980's & Beyond. Prepared by the National Science Foundation and the Department of Education; October 1980.

	Projected Job Openings 1978-1990	Projected Graduates 1978-1990	Projected Surplus (Shortfall)
Chemical Engineering	22,000	92,000	70,000
Civil Engineering	95,000	134,000	39,000
Electrical & Computer Engineering	121,000	172,000	51,000
Industrial Engineering	94,000	48,000	(46,000)
Mechanical Engineering	89,000	171,000	82,000

SOURCES: National Science Foundation, Bureau of Labor Statistics, National Center for Education Statistics.

A tabulation of IE programs in the most recent ABET report of accredited curricula* shows 79 IE programs. This places IE fifth, following the other major engineering disciplines of Electrical (218), Mechanical (199), Civil (178), and Chemical (129).

*Accreditation Board for Engineering and Technology, 49th Annual Report; September 30, 1981.

II. DEFINITIONS

Examination of Figure 1 reveals that the IE discipline has roots in many diverse basic and applied sciences: mathematics, probability/statistics, behavioral sciences, economics, physiology, etc. The diversity of the IE foundation lends strength to IE as a major, unique engineering discipline.

The principal activity engaged in by engineers that distinguishes them from other professionals is that of the design of systems. Basic courses in engineering science (which are based on mathematics and basic sciences) are taken by all engineering students to provide a general foundation upon which design principles in specific engineering specialty curricula are later built.

Mechanical engineers design systems that are primarily mechanical in nature. Electrical engineers design the electrical components of systems.

It follows, then, that industrial engineers design "industrial" systems, but "industrial" must be defined to include all types of organizations, not just manufacturing.

Industrial engineers design systems at two levels. The first level is called human activity systems and is concerned with the physical workplace at which human activity occurs. The second level is called management control systems and is concerned with procedures for planning, measuring, and controlling all activities within the organization.

Compared to other engineering disciplines, the design methodology for industrial engineering is relatively primitive. Even though it can truthfully be argued that the systems with which IE's deal are much more complex than purely mechanical or electrical systems, satisfactory progress in developing design methodology has not been made. Much research effort needs to be directed toward the development of better design procedures.

A. Definitions of Science/Engineering

Science (Dictionary Definition)* - systematized knowledge derived from observation, study, and experimentation carried on in order to determine the nature or principles of what is being studied; a branch of knowledge or study, especially one concerned with establishing and systematizing facts, principles, and methods, as by experiments and hypotheses.

(ABET)** - In a study of basic sciences, the objective is to acquire fundamental knowledge about nature and its phenomena, preferably including quantitative expression.

Engineering (ABET) - the profession in which a knowledge of the mathematical and natural sciences gained by study, experience, and practice is applied with judgment to develop ways to utilize, economically, the materials and forces of nature for the benefit of mankind.

Engineering Science (ABET) - Engineering sciences have their roots in mathematics and basic sciences, but carry knowledge further toward creative application. When a field of mathematics or basic science proves pertinent to an engineering application, there develop corresponding courses in engineering science to afford a bridge between the basic science and engineering practice.

Engineering Design (ABET) - the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet

---

* Webster's New World Dictionary of the American Language, 1976.

**Adapted from Accreditation Board for Engineering and Technology, 49th Annual Report; September 30, 1981.

a stated objective. Central to the process are the essential and complementary roles of synthesis and analysis.

B. Definition of Industrial Engineering

Industrial Engineering (IIE)* - Industrial engineering is concerned with the design, improvement, and installation of integrated systems of people, material, equipment, and energy. It draws upon specialized knowledge and skills in the mathematical, physical, and social sciences together with the principles and methods of engineering analysis and design to specify, predict, and evaluate the results to be obtained from such systems.

It is noted that this definition of IE has withstood the "test of time," having required only very minor amendments since its original adoption, even though the IE role and application areas have changed substantially.

*Approved by IIE Board of Trustees; last amended 10/28/78.

III. IE FUNCTIONS, TOOLS AND UNDERLYING SCIENCE BASE

Having established the essential role of IE within the engineering profession, it is now important to discuss the relationship between IE functions (what IE's do), IE tools (methodologies for performing functions), and the underlying IE science base (knowledge, principles, and fundamentals upon which IE tools are based).

Figure 2 is included to assist in visualizing these relationships. This illustration can be considered a "map" which shows the progression from fundamental knowledge to specific applications. The example included on Figure 2 illustrates how any specific IE function can be mapped back to the tools needed to perform the function, and finally to the science base (underlying principles, knowledge and concepts) upon which the tools are based.

Industrial engineers in both academia and professional practice are engaged in Research and Development activities aimed at developing new tools, methodologies, principles, and knowledge for the advancement of the profession. The scope of research and development activities is extremely broad, touching all aspects of the IE profession.

As with all scientific and engineering disciplines, most progress in IE research comes through small incremental advancements rather than through dramatic breakthroughs. IE research is complicated by the fact that two of the most prominent factors with which IE's must contend, human behavior and economics, are highly variable and unpredictable.

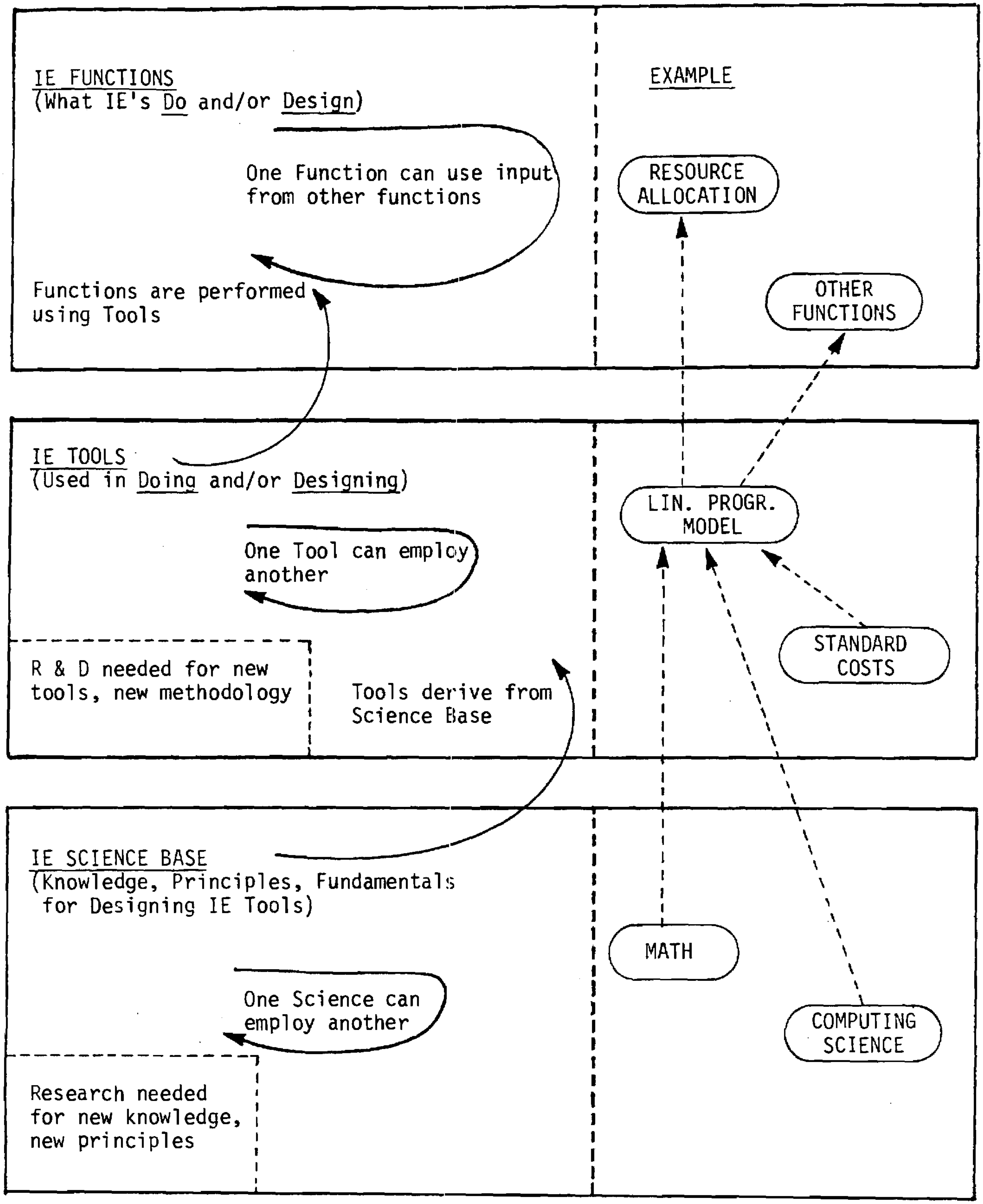

Figure 2. Relationship Between IE Functions, IE Tools and the Underlying IE Science Base

IV. IE FUNCTIONS

An attempt has been made to develop a comprehensive set of functions that IE's perform in the world of work. The authors arbitrarily grouped the functions according to the ten Systems Engineering and Technical Divisions of IIE, plus one more grouping titled "Management and Industrial and Labor Relations." The resulting eleven groupings are:

Computer and Information Systems
Energy Management
Engineering Economy
Ergonomics
Facilities Planning and Design
Management and Industrial and Labor Relations
Manufacturing Systems
Operations Research
Production and Inventory Control
Quality Control and Reliability Engineering
Work Measurement and Methods Engineering

This set of groupings proved to be adequate for classifying industrial engineering activities. Furthermore, the authors are confident that a large percentage of IE functions have been identified.

Functions are stated in a fairly general manner, attempting to identify those <u>major activities</u> which practicing IE's are responsible for performing. Activities which the authors viewed as being outside the main stream of IE were omitted.

As the authors began listing IE activities in the eleven groupings, a consistent pattern began to merge. Within each major grouping, IE functions were further subdivided into the following four phases:

Analysis

Design

Implementation

Management and Control

The comprehensive set of IE functions is presented in Tables F.1 through F.11 of the Appendix. The reader will notice the high degree of similarity on all tables of the last two phases, "Implementation," and "Management and Control."

V. IE TOOLS

This section presents a comprehensive set of tools which are available to IE's for performing their functions in the world of work. A decision had to be made whether to group the tools in accordance with the function groupings, or to group them according to the science base groupings. It was decided to group the tools consistent with the function groupings, since tools exist to perform certain functions and not as ends in themselves.

A WORD OF CAUTION:

The listing of tools found in Tables T.1 through T.11 in the Appendix are uneven in terms of level of detail involved. Since no two IE's can possibly be aware of all the latest tools available across the profession, the authors were forced to use general groupings in many places. Furthermore, no claim is made regarding the comprehensiveness of these lists. This document should be considered a point of departure. Nevertheless, it is hoped that the major categories of tools on which IE R&D people are working have been included.

VI. IE SCIENCE BASE

As was mentioned earlier, the IE discipline has roots in many diverse basic and applied sciences. The authors have attempted to identify a comprehensive set of concepts, principles, and fundamentals upon which IE Tools/Methodology are based. The science areas can be grouped as shown in Figure 3.

Tables S.1 through S.14 in the Appendix contain the science base elements.

BASIC SCIENCES

- Physics
- Chemistry
- Physiology

SOCIAL AND BEHAVIORAL SCIENCES

- Psychology
- Sociology
- Economics

ABSTRACT AND QUANTITATIVE THOUGHT

- Mathematics
- Probability and Statistics
- Philosophy
- Information Science
- Computing Science
- Systems Science

ENGINEERING SCIENCES

- Materials Science
- Thermodynamics and Heat Transfer
- Electrical Science
- Statics and Strength
- Dynamics
- Fluid Mechanics

SCIENCES OF ENGINEERING DISCIPLINES

- Operational and Decision Sciences (Related to Industrial Engineering)

(Sciences related to other engineering disciplines not listed.)

Figure 3. Classification of Science Areas Pertinent to IE

APPENDIX

Tables for Functions	:	F.1 through F.11
Tables for Tools	:	T.1 through T.11
Tables for Sciences	:	S.1 through S.14

COMPUTERS & INFORMATION SYSTEMS

(Functions)

Analysis

Assessing State of the Art in C&IS
Define Decision Structure of Organization/Output Report
Determine Information Requirements (Routing, Volume, Type, Frequency)
Determine On-Line Process Control Requirements
Assessing Equipment/Software Capabilities vs. Requirements
In-house vs. Vendor Analysis
Space and Environment Requirements
Networking/Telecommunication Considerations
Evaluation of Alternative Computer and Information Systems
Internal and External Regulatory Constraints
Interactive Access Requirements
Strategic Planning

Design

Data Acquisition System
Data Verification Procedures
Data Assimilation System
Data Reduction/Processing Procedures
Data/Information Transmission System
Data Bases
System Validation/Backup Procedures
Output Reports/Distribution
Interactive Processing System
Feedback to On-Line Processes
Operating/Control System
Policies, Procedures
Detailed Implementation Plan

Implementation

Justification and Promotion of Design
Obtaining Management Approval and Commitment
Obtaining Budgetary Support
Communication of Plans to All Concerned
Agreement on System Performance Measures
Forms, Format Design
Detailed Procedures and Documentation
System Test, Validation (Bench Mark Testing)
Modifications to Design
Training and Education Activities
Supervision of Transition Activities and Implementation Plan

COMPUTERS & INFORMATION SYSTEMS

(Functions)

Analysis

Assessing State of the Art in C&IS
Define Decision Structure of Organization/Output Report
Determine Information Requirements (Routing, Volume, Type, Frequency)
Determine On-Line Process Control Requirements
Assessing Equipment/Software Capabilities vs. Requirements
In-house vs. Vendor Analysis
Space and Environment Requirements
Networking/Telecommunication Considerations
Evaluation of Alternative Computer and Information Systems
Internal and External Regulatory Constraints
Interactive Access Requirements
Strategic Planning

Design

Data Acquisition System
Data Verification Procedures
Data Assimilation System
Data Reduction/Processing Procedures
Data/Information Transmission System
Data Bases
System Validation/Backup Procedures
Output Reports/Distribution
Interactive Processing System
Feedback to On-Line Processes
Operating/Control System
Policies, Procedures
Detailed Implementation Plan

Implementation

Justification and Promotion of Design
Obtaining Management Approval and Commitment
Obtaining Budgetary Support
Communication of Plans to All Concerned
Agreement on System Performance Measures
Forms, Format Design
Detailed Procedures and Documentation
System Test, Validation (Bench Mark Testing)
Modifications to Design
Training and Education Activities
Supervision of Transition Activities and Implementation Plan

Management and Control

Periodic, Scheduled Review of System Performance
(Quantity, Quality, Cost, Satisfaction)
Review of Hardware/Software Supplier Performance
Reaction and Response to Unanticipated Perturbations
Initiation or Cooperation with Problem Solving Teams and Activities
Short Term Corrective Action
Long Term Corrective Action
Follow-up on Corrective Action
Monitoring Technological Innovation
System Updates and Improvements
Maintenance of Data Base, Operating System, Operating Procedures

ENERGY MANAGEMENT

(Functions)

Analysis

Assessing State of the Art in Energy Management Practice
Analysis of Energy Content in Raw Materials
Design Review for Energy Content of Components (Reduce Material Mass, Material Substitution, Material Treatment)
Analysis of Energy Consumption in Processes (Fabrication, Assembly, and Other Processes)
Assessment of Work Methods for Energy Conservation
Analysis of Energy Consumption in Facilities
Analysis of Energy Consumption in Transportation and Distribution
Analysis of In-Plant Energy Conversion Processes (Boilers and Fired Systems; Steam and Condensate Systems)
Recognition of Energy Management Control Systems Potential
Recognition of Co-generation and Waste Heat Recovery Potential
Consideration of Alternative Energy Sources

Design

Comprehensive Energy Management Program
Product Redesign
Process Redesign
Facilities Redesign
Transportation and Distribution System Redesign
Redesign of In-Plant Energy Conversion Processes
Design of Energy Management Control Systems
Design of Co-generation and Waste Heat Recovery Facilities
Design of Processes to Accomodate Alternative Energy Sources
Energy Conservation Awareness Program
Detailed Implementation Plan

Implementation

Cost-Benefit Justification
Promotion of Design Decisions
Obtaining Management Approval and Commitment
Obtaining Budgetary Support
Communication of Plans to All Concerned
Agreement on System Performance Measures
Forms and Format Design
Detailed Procedures and Documentation
System Test, Validation
Modifications to Design
Training Activities
Supervision of Transition Activities and Implementation Plan

Management and Control

Periodic Scheduled Review of System Performance
Reaction and Response to Unanticipated Perturbations
Initiation and Coordination of Problem Solving Teams
Short Term Corrective Action
Long Term Corrective Action
Follow-up On Corrective Action
Maintenance of Data Base
Monitoring Technological Innovations
System Updates and Improvements

ENGINEERING ECONOMY

(Functions)

Analysis

Supply, Demand and Competition
Direct Labor, Material and Equipment Needs
Auxilliary Supplies and Resource Needs
Time-Phased Investment, Operation, and Maintenance
Constraints
Cost Estimating
Capital Availability and Cost Projection
Cash Flow Analysis
Alternative Evaluation (Including Replacement Analysis)
Cost/Benefit Analysis
Cost Effectiveness Analysis
Portfolio Analysis

Design

Capital Budgeting
Capital Acquisition Plan
Budgeting and Cash Flow Plan
Pricing Strategies
Cost Collection and Reporting System
Alternative Evaluation Procedures

Implementation

Cost Justification
Obtaining Management Approval and Commitment
Obtaining Budgetary Support
Communication of Budget to Appropriate Management
Agreement on Measures of Economic Merit
Detailed Cost Collection Form, Format, Procedure Design
Modification of Budget and Cash Flow Projection
Economic Analysis Forms, Formats
Economic Analysis Training

Management and Control

Periodic Review and Projection of Economic Measures of Merit
Notification of Appropriate Management Concerning Unanticipated Perturbations
Initiation and Coordination of Cost Reduction Programs
Auditing of Data Collection and Alternative Evaluation Procedures
Follow-up on Projections in Problem or High Cost Areas
Monitoring of Outside Market and Financial Conditions
Modernization of Data Collection, Analysis, and Communication System

ERGONOMICS

(Functions)

Analysis

Surveillance of Work Environment for Problems and Opportunities
Physiological, Psychological, and Mental Characteristics of Workforce
Sociological Requirements of Workforce
Work Content Analysis of Tasks
Information Requirements of Tasks (Input and Feedback)
Process Control Requirements
Occupational Safety, Health, Hygiene, and Welfare of Workers
Analysis of Human/Machine Interface

Design

Tasks and Jobs
Workplaces
Equipment, Processes, and Controls
Tools and Devices
Work Environment
Allocation of Functions Between Humans and Machines
Safety and Health Devices
Health and Safety Policies and Procedures
Human-Involved Information Transfer
Training Programs
Physical Fitness Programs
Implementation Plan

Implementation

Cost-Benefit Justification
Obtaining Management Approval and Commitment
Obtaining Budgetary Support
Communication of Programs and Plans to All Concerned
Agreement on System Performance Measures
Forms, Format Design
Detailed Procedures and Documentation
Fitting the Individual to the Job
System Test, Validation
Modifications to Design
Training and Education Activities
Supervision of Transition Activities and Implementation Plan

Management and Control

Periodic, Scheduled Review of System Performance
Reaction and Response to Unanticipated Perturbations
Initiation and Coordination of Problem Solving Teams and Activities
Short Term Corrective Action
Long Term Corrective Action
Follow-up on Corrective Action
Monitoring of Work Environment
System Updates and Improvements
Maintenance of Data Base (Including Research Literature)

FACILITIES PLANNING AND DESIGN

(Functions)

Analysis

Production Volume Projections
Facility Type and Capacity
Facility Location Analysis
Regulatory Constraints
Construction Technology Considerations
Machine Groupings and Operations Sequencing
Determining Departmental Relationships
Inter-departmental Flows
Aisle Requirements
Alternative Layout Analysis
Environmental, Health/Safety Considerations
Equipment Sizes and Geometry
Auxillary Supplies and Resource Space Requirements
Utility Needs and Routing
Materials Handling Considerations
Incoming, In-process, and Final Product Storage
Maintenance Considerations

Design

Facility Location Decision
Iterative Facility Layout Process/Decision
Material Handling System Decision
Facility Construction Decision
Detailed Implementation Plan
Land Acquisition and Preparation Plan
Construction Specifications/Requirements; Request for Bids
Equipment Acquisition Plan
Comprehensive Cash Flow Plan
Project Schedule and Control Plan

Implementation

Cost Justification
Obtaining Management Approval and Commitment
Obtaining Budgetary Support
Communication of Plans to All Concerned
Agreement on Project Time and Cost Schedule
Agreement on System Performance Measures
Detailed Plans and Documentation
System Test, Validation
Modifications to Design
Project Management

Management and Control

Periodic Scheduled Review of System Performance
Reaction and Response to Unanticipated Perturbations
Initiation and Coordination of Problem Solving Teams
Short Term Corrective Action
Long Term Corrective Action
Follow-up on Corrective Action
Monitoring Technological Innovation
System Updates and Improvements

MANAGEMENT; INDUSTRIAL & LABOR RELATIONS

(Functions)

Analysis

Competitive Environment - Company/Company
Competitive Environment - Company/People
Competitive Environment - People/People
Needs, Attitudes, and Capabilities of Personnel
Skills & Aptitudes Required by Organization
Financial Viability and Requirements of Organization
Information Flow Requirements
Regulatory Constraints
Job Evaluation
Strategic Planning

Design

Organization Design
Job Design/Descriptions
Communication System
Management Decision Aids
Managerial Accounting & Budgetary Control Systems
Policies & Procedures
Labor Relations Programs
Wage and Salary Programs
Incentive Plans
Human Resources Development Programs
Detailed Implementation Plan

Implementation

Justification and Promotion of Design
Obtaining Management Approval and Commitment
Obtaining Budgetary Support
Communication of Plans to All in Organization
Management and Operational Level Agreement on System Performance Measures
Forms, Format Design
Detailed Procedures and Documents
System Test, Validation
Modifications to Design
Training Activities
Supervision of Transition Activities and Implementation Plan

Management and Control

Periodic, Scheduled Review of System Performance
Reaction and Response to Unanticipated Perturbations
Initiation and Coordination of Problem Solving Teams and Activities
Short Term Corrective Action
Long Term Corrective Action
Follow-up on Corrective Action
Monitoring "Environment"
System Updates and Improvements
Maintenance of Data Base

MANUFACTURING SYSTEMS

(Functions)

Analysis

Product and Service Design Review
Value Analysis
Producibility
Material Assessment
Production Volume Considerations
Make/Buy Analysis
Determine On-Line Process Control Requirements
Process Capability/Capacity Analysis
Automation/NC/CAD/CAM/Robotic Considerations
Evaluation of Alternative Operation Sequences
Production Time Analysis
Auxillary Supplies and Resource Needs
Labor Needs
Regulatory Constraints
Manufacturing Cost Analysis
Test Equipment Analysis
Materials Handling Analysis
Facility Layout Analysis
Buffer Storage Requirements

Design

Final Product Design
Materials and Purchased Item Specifications
Machine Groupings and Operations Sequencing
Process Design Specifications
Flow Line Balances
Inspection and Test Points
Inspection and Test Equipment Selection
Shop Floor Controls
Process-to-Process Information Transfer
Materials Handling Equipment Selection
Maintenance Policies and Procedures
Detailed Implementation Plan

Implementation

Obtaining Management Approval and Commitment
Obtaining Long Term Phased Budgetary Support
Communication of Plans to All Involved
Agreement of Product, Service, and/or System Performance Measures
Forms, Format Design
Detailed Procedures, Documentation, Instructions

Automation/NC/CAD/Robotic Programming
Initial Production Test, Validation
Modifications
Training Activities
Supervision of Start-up Activities and Implementation Plan

Management and Control

Periodic, Scheduled Review of System Performance
(Quantity, Quality, Cost)
Reaction and Response to Unanticipated Perturbations
Initiation and Coordination of Problem Solving Teams and Activities
Short Term Corrective Action
Long Term Corrective Action
Follow-up Corrective Action
Monitoring Technological Innovation
(Equipment, Communications, Materials, Energy)
System Updates and Improvements

OPERATIONS RESEARCH

(Functions)

Analysis

Surveillance of External Forces, Events and Conditions
General Economy, Markets, Competition, Suppliers, Resources
Surveillance of Internal Operations to Identify Targets of Opportunity
Acquire Thorough Understanding of Specific Problem or Project
Determine Specific Objectives
Determine Constraints Over Which Organization Has No Control
Determine and Question Other Perceived Constraints
Model Requirements
Model Selection or Decision to Develop Model
Information Requirements
Computation Requirements Vis-A-Vis Capacities

Design

Data Acquisition Plan
Data Verification Procedures
Identification and Statement of Assumptions
Model Development or Adaptation
Model Validation Procedures
Strategies for Model Use
Optimization Procedures
Deriving Model Results
Interpretation of Model Results
Interaction With Client
Sensitivity Analysis/Parametric Programming
Resource Tradeoff Considerations
Development and Refinement of OR Methodology

Implementation

Justification of Recommendations
Providing Information for Management Approval and Commitment
Obtaining Budgetary Support
Communication of Plans to All Concerned
Agreement on Measures of Merit Resulting from Model Implementation
Modification to Design Due to Changes in Objectives and Constraints
Forms, Format Design
Detailed Procedures and Documentation
System Test, Validation, Modifications
Recommendation of Implementation Plan

Management and Control

Periodic, Scheduled Review of Pertinent Performance Measures
Formation of Interdisciplinary OR Team as Needed
Recommendation of Reaction and Response to Unanticipated
Perturbations
Maintaining Model and Updating Data Base
Follow-up on Corrective Action
Monitoring of OR Methodology Development
Monitoring of Computational Software and Hardware

PRODUCTION AND INVENTORY CONTROL

(Functions)

Analysis

Analysis of Factors Affecting Demand
Consideration of Time, Cost, and Materials Estimates
Manufacturing Requirements Planning
Financial Analysis of Operating Plans
Consideration of Improvement Curve
Raw Material, In-Process, Finished Goods Inventory Analysis
Review/Revision of Operation Sequences, Line Balances, Production Rates
Consideration of Capacities, Current Workload
Operational Considerations in Inventory Control, Production Scheduling

Design

Demand Forecast by Period
Strategic Operations Plan
Master Production Schedule (Production Smoothing)
Inventory Control Sub-System (for Manufactured and Purchased Items)
Short Term Schedule
Project Schedules
Production Initialization Sub-System
Shop Floor Control Sub-System (Data Acquisition, Performance Evaluation, Short Term Corrective Action)
Integrated Production Planning and Control System
Detailed Implementation Plan

Implementation

Cost Justification
Obtaining Management Approval and Commitment
Obtaining Budgetary Support
Communication of Plans to All Concerned
Agreement on System Performance Measures
Forms, Format Design
Computer Programming, Debugging; Interfacing with Total Company Information Processing Systems
Detailed Procedures, Documentation, Instructions
System Test, Validation
Modifications
Training Activites
Supervision of Transition Activites and Implementation Plan
Project Management

Management and Control

Periodic, Scheduled Review of System Performance
Reaction and Response to Unanticipated Perturbations
Cooperation with Problem Solving Teams and Activities
Short Term Corrective Action
Long Term Corrective Action
Follow-up on Corrective Action
Monitoring Technological Innovation (Equipment, OR Techniques, Systems Concepts, Communications Developments)
Maintenance of Data Base
System Updates and Improvements

QUALITY CONTROL AND RELIABILITY ENGINEERING

(Functions)

Analysis

Fitness for Use Criteria
Product or Service Design Review
Performance, Reliability, and Maintainability Analysis/Prediction
Ability to Perform Inspection and Test
Vendor Evaluation and Qualification
Instrumentation, Gage, and Equipment Needs
Process Capability Analysis
Inspection and Test Requirements
Calibration System Requirements
Handling, Packaging, Transportation, and Storage Needs
Field Service Requirements

Design

Final Product or Service Design
Design Review Process
Vendor Evaluation System
Inspection and Test Point Selection
Inspection and Test Criteria
Process Surveillance and Control Criteria
Data Collection and Analysis Procedures
Quality Cost System
Quality Policies and Objectives
Quality Organization
Quality Program
Traceability of Material/Product
Motivation Program
Training Program
Detailed Implementation Plan

Implementation

Obtaining Management Approval and Commitment
Obtaining Budgetary Support
Communication of Plans to All Involved
Agreement on Product, Service, and/or System Performance Measures
Inspection and Test Instructions and Standards Documentation
Process Surveillance Instructions and Standards Documentation
Quality Reporting Forms, Format Design
Quality Program Documentation in Quality Manual
Quality Cost Collection Transfer to Accounting
Training Activities
Supervision of Start-up Activities and Implementation Plan
Modifications to Design

Management and Control

Inspection and Test Data Collection, Analysis, and Review
Process Surveillance Data Collection, Analysis, and Review
Quality Cost Analysis and Review
Initiation and Coordination of Problem Solving Teams and Activities
Solving Sporadic Problems
Solving Chronic Problems
Establishing and Maintaining Operator Controllability
Monitoring Inspection Integrity
Monitoring Field Service Problems
Feedback of Results to Appropriate Areas
Follow-up on Corrective Action
Maintenance of Data Base

WORK MEASUREMENT AND METHODS ENGINEERING

(Functions)

Analysis

Analysis of Product/Process Specifications and Operations
Determine Fundamental Work Operations and Flow Sequences
Analysis of Flow Process Charts
Analysis of Time Study Data
Applying the Rating Factor and Allowances
Determine Opportunities for Savings Through Improvements
In: Product Design; Manufacturing Processes; Operations Management; Worker Performance

Design

Construct Operations Process Charts
Determine Preferred Methods
Construct Flow Process Charts
Synthesize Standard Operation Times
Design Work Measurement Procedures, Policies, and Programs
Workplaces
Tools and Devices
Work Environment
Training Programs
Standards Data Base

Implementation

Cost-Benefit Justification
Obtaining Management Approval and Commitment
Obtaining Budgetary Support
Communication of Plans to All Concerned
Agreement on System Performance Measures
Operator Instructions
Detailed Procedures and Documentation
Fitting the Individual to the Job
System Test, Validation
Modifications as Required
Training and Education Activities
Supervision of Transition Activities and Implementation

Management and Control

Periodic, Scheduled Review of System Performance
Reaction and Response to Unanticipated Perturbations
Initiation and Coordination of Problem Solving Teams and Activities
Short Term Corrective Action
Long Term Corrective Action
Follow-up On Corrective Action
Monitoring Operations Environment
System Updates and Improvements
Maintenance of Data Base (Auditing Standards)

COMPUTERS AND INFORMATION SYSTEMS

(Tools)

Tools from Engineering Economy

Tools for Analyzing Information Needs of Organization

- Analysis of Organization's Decision Structure
- Procedures for Determining Information Flow Rates

Tools for Designing Data Acquisition Sub-System

- Micro-processors, Direct Digital Control Methods
- Remote Input Stations
- Telecommunications Systems/Processes

Tools for Designing Data Verification/Assimilation Sub-System

- Data Verification Schemes
- Concepts of Hash Totals, Cross Totals
- Concepts and Procedures from Accounting
- Procedures for Updating Master Data Bases

Tools for Designing Data Reduction/Processing Sub-System

- Statistical Tools/Analysis Procedures
- Optimization Codes
- Program Libraries
- Numerical Methods and Error Analysis
- Applications Packages

File Processing Techniques

- Sorting Techniques
- Search Techniques
- Merge Techniques
- Updating and Retrieval Methods
- String Processing Methods

Tools for Designing Data/Information Transmission Sub-System

- Feedback Procedures to On-Line Processes
- Interactive Inquiry/Modeling

Tools for Designing Output Reports/Distribution Sub-Systems

- Report Generators
- Telecommunications Systems/Processes

Programming Languages

- Assemblers
- Interpreters
- Higher Level Languages
- Simulation Languages
- Report Generator
- Non-numerical Algorithms
- Data Base Languages/Systems

Microcomputer Application Packages

Math/Stat Packages

Large Scale Optimization Techniques

Security Access Methods

Distributed Computing Methodology

Computer Networking Techniques/Systems

Word/Text Processing Techniques/Systems

ENERGY MANAGEMENT

(Tools)

Product Design Review and Value Analysis

Tools from Behavioral Sciences to Influence Energy Usage

Tools from Engineering Economy

Basic Energy Data Base

Energy Audit Procedures

- Energy Measuring Devices/Procedures
- Field/Site Data Gathering
- Procedures for Analyzing Audit Data
- Economic and Non-Economic Factor Analysis
- Procedures for Implementing and Monitoring Audit Results

Analytical Techniques in Energy Management

- Incremental-Cost Concept
- Mass and Energy Balancing Techniques
- Inventory of Energy Inputs, Consumption, Rejections
- Heat-Transfer Methodologies
- Electrical Load Characteristic Procedures

Computer Simulation Models for Energy Management

Tools/Techniques for Energy Management for Specific Functions

- Boilers and Fired Systems
- Steam and Condensate Systems
- Cogeneration
- Waste-Heat Recovery
- Building Envelope
- Heating, Ventilating, and Air Conditioning
- Lighting
- Electric Energy Management
- Insulation
- Vehicle Fleet Management

Automated Energy Management Systems

Energy Systems Maintenance Procedures

Procedures for Evaluating Use of Alternative Energy Sources

ENGINEERING ECONOMY

(Tools)

Tools for Assessing Competitive Environment

Mutual-Benefit Concept

Cost Estimation and Control Tools

- Accounting Principles
- Cost Terminology and Classification
- Operating Budgets
- Cost Accounting Records and Statements
- Cost Estimation Procedures
- Overhead Allocation Methods
- Life-Cycle Costing Concept
- Auditing Procedures

Time Value of Money Concepts

- Inflation Concepts
- Cash Flow Profiles
- Cost of Capital Calculation Methods
- Compounding Methods
- Equivalence Concepts and Methods
- Interest Formulas and Factors

Models for Economic Regulation

Depreciation Accounting Methods

Income Tax Regulations and Strategies

Methods for Alternative Evaluation and Project Selection

- Methods for Formulating Mutually Exclusive Alternatives
- Methods for Defining the Planning Horizon
- Discounted Cash Flow Analysis Procedures
- Rate of Return Procedures
- Payout Period Procedures
- Specialized Replacement Analysis Rules
- Cost/Benefit Methods
- Cost-Effectiveness Methods
- Break-Even Techniques
- Minimum Cost Techniques

Tools for Decision Making Under Risk

- Expected Value and/or Variance Tools
- Decision Trees
- Monte Carlo Methods
- Utility Theory

Tools for Decision Making Under Uncertainty

- Payoff Matrix
- The Laplace Rule
- Maximin, Minimax, etc., Rules
- Minimax Regret Rule
- Hurwicz Rule
- Utility Theory

Capital Budgeting and Portfolio Selection Tools

Table T.4

ERGONOMICS

(Tools)

Anthropometric Data

Other Tables Representing Knowledge Base from Ergonomics Research

Fault Tree Analysis

Equipment Mockups

Simulation Using Iconic Models

Physiological Measuring Devices and Procedures

Physiological Stimulus Devices and Procedures

Environmental Measuring Devices and Procedures

Environmental Control Devices and Procedures

Task Analysis Procedures

FACILITIES PLANNING AND DESIGN

(Tools)

Tools for Facility Location

- Location Factor Analysis (Checklists, Weighting Schemes)
- Quantitative Techniques for Single Facility Location Problems
- Quantitative Techniques for Multi-Facility Location Problems
- Location-Allocation Procedure
- Simulation Models for Facility Location

Tools for Facility Design/Layout

- Tools from Manufacturing Engineering
- Tools from Production and Inventory Control
- Computer Aided Process Planning Methods
- Procedures and Techniques for Designing Material Flow
- Activity Relationship Charts
- Computer Aided Layout Techniques
- Procedures for Designing Material Handling System
- Quantitative Techniques for Facility Layout
- Scale Models

Tools for Facility Construction

- PERT/CPM
- Total Facility Conversion/Move Plan
- Time Phased Budget for Construction

MANAGEMENT; INDUSTRIAL AND LABOR RELATIONS

(Tools)

Tools for Strategic Planning

- Technological Forecasts
- Opportunistic Surveillance of Environment
- Procedures for Assessing Competitive Position
- Procedures for Assessing Internal Strengths, Weaknesses
- Management by Key Results/Objectives

Decision Aids

- Decision Theory
- Quantitative Decision Methods (Tools from O.R. and Stat.)
- Heuristics, Decision Rules
- Simulation Models, Interactive Modeling
- Group Decision Processes

Tools for Organization Design

- Procedures for Organizational Analysis, Departmentalization
- Group Process Techniques
- Procedures Relating to Situational Leadership

Tools for Human Resource Development

- Testing Procedures, Measurement Devices
- Selection/Placement Procedures
- Training Programs
- Methods for Professional Development
- Procedures for Counseling Employees

Procedures for Job Design, Job Descriptions

Procedures for Designing Wage and Salary Programs

- Job Classification Schemes
- Wage and Salary Surveys

Procedures for Designing Incentive Programs and Strategies

- Incentive Plans, Gainsharing Programs
- Worker Involvement Strategies
- Productivity Measurement Procedures
- Quality Circle Programs

Procedures for Financial Management and Control

Managerial Accounting Procedures
Budgetary Analysis and Control Systems
Financial Ratio Analyses
Capital Budgeting, Project Evaluation Techniques
Portfolio Analysis Procedures

MANUFACTURING SYSTEMS

(Tools)

Product Design Review and Value Analysis

Tools from Engineering Economy

Layout and Materials Handling Methodology

Routing and Sequencing Algorithms

Assembly Line Balancing Methods

Production Systems Simulation Models

Optimization of Individual Operations

- Cutting Speeds, Feeds
- Cutting Tool Material Selection
- Decision Procedures for Operation/Equipment Selection
- Human/Machine Interface Procedures

Numerical Control Methodology/NC Programming

CAD/CATO/CAM/CAT Methodology

Process Monitoring Methodology

Process Control Methodology (Digital and Direct Analog Control)

- Transfer Functions, Block Diagrams
- Laplace Transforms
- Linear Systems Analysis
- Root-Locus Method
- Steady-State Optimal Control
- Adaptive Control
- On-Line Search Strategies
- EVOP (Evolutionary Operations)

Methodology for Manufacturing Support

- Time Standards Data Structures
- Machinability Data Systems
- Cutting Conditions Optimization
- Production and Inventory Planning Tools
- Materials Requirements Planning (MRP)

Group Technology Tools

- Parts Classification and Coding Schemes
- Production Flow Analysis
- Machine Cell Design Procedures

Automated Process Planning Methodology

Automatic Assembly

Flexible Manufacturing System Methodology

Automated Warehouse

OPERATIONS RESEARCH

(Tools)

Classical Optimization/Mathematics

Mathematical Programming

- Linear
- Integer
- Mixed-Integer
- Goal and Multi-objective
- Nonlinear
- Dynamic
- Geometric
- Stochastic

Branch and Bound Techniques

Search Techniques

Queueing Theory/Models

Inventory Theory/Models

Decision and Game Theory/Models

Network and Flowgraph Theory/Models

Simulation

- Languages
- Variance Reduction Techniques
- Monte Carlo Theory

Heuristics

Stochastic Processes

Parametric/Sensitivity Procedures

PRODUCTION AND INVENTORY CONTROL

(Tools)

Forecasting Tools

- Averaging and Smoothing Methods
- Time Series and Spectral Analysis
- Adaptive Forecasting Methods
- Bayesian Methods in Forecasting

Operations Planning Tools

- Time Balancing Algorithms
- Manufacturing Resources Planning (MRPII)
- Matrix and Mathematical Programming
- Production and Workforce Smoothing
- Linear Decision Rule
- Capacity Requirements Planning
- Learning (Improvement) Curve

Inventory Planning and Control Tools

- Economic Order/Manufacture Quantity Models
- Materials Requirement Planning (MRP)
- Multiple-Item Replenishment Methods
- In-Process Buffer Size Models
- Multi-echelon Inventory Models
- Sequential Optimization Methods
- Inventory Review/Control Methods

Operations Scheduling Tools

- Facility Loading Techniques
- Task Sequencing Algorithms
- Flow-Shop Scheduling Methods
- Job-Shop Scheduling Methods
- Scheduling Algebras
- Scheduling Heuristics

Project Scheduling and Control

- Network Scheduling Methods
- Cost/Time Methods
- Multi-Project Scheduling Methods
- Resource Allocation in Project Networks

Production Initialization and Shop-Floor Control

Integrated System for Production Order/Material/Tool Release Orders
Data Collection/Integration/Analysis Procedures
Statistical Procedures for Performance/Status Evaluation
(Much developmental work in Computer Aided Manufacturing is critically needed for this function.)

QUALITY CONTROL AND RELIABILITY ENGINEERING

(Tools)

Product Design Review Procedures

- Specification and Tolerancing Tools
- Reliability Apportionment, Prediction, and Analysis
- Design Review Techniques
- Failure Mode and Effects Analysis
- Fault Tree Analysis

Product Appraisal and Conformance Control

- Product Characteristic Classification
- Process Flow Charts
- Inspection and Test Procedures
- Sampling Plans and Procedures
- Statistical Inference and Estimation
- Product Audit Procedures
- Nonconformance Disposition Procedures

Process Control Tools

- Identification Systems for Traceability
- Process Flow Charts
- Control Charts
- Narrow Limit Gaging: PRE Control
- Process Capability Analysis Methods
- Design of Experiments and Analysis of Variance
- Response surface methodology
- Evolutionary Operations
- Process Quality Audit Procedures
- Statistical Inference and Estimation
- Probability Theory
- Operation Controllability Procedures
- Setup/Machine/Operator/Component Dominance Techniques

Quality Assurance Managment Tools

- Quality Policy and Procedures Manual
- Quality Cost Systems
- Pareto Analysis Techniques
- Economic Analysis Procedures
- Calibration Assurance Procedures
- Monitoring and Analyzing Field Usage Data
- Data Collection/Integration/Analysis Procedures
- Quality Audit

WORK MEASUREMENT AND METHODS ENGINEERING

(Tools)

Data from Ergonomics

Tools for Analyzing Work Methods

- Operation Process Chart
- Flow Process Chart
- Human/Machine Process Charts
- Gang Process Charts
- Quantitative Techniques for Human/Machine Relationships
- Operator Process Charts

Methods Design Process

- Tools for Formulating and Analyzing Methods Design Problems
- Alternative Search Procedures
- Procedures for Evaluating Alternatives
- Procedures for Documenting the Method Design
- Procedures for Implementation and Review
- Job Enlargement Considerations

Tools for Motion Analysis

- Motion Classification Schemes
- Principles of Motion Economy
- Micromotion Study Procedures

Tools for Work Measurement

- Time Study Devices/Procedures
- Performance Rating Procedures
- Allowance Application Procedures
- Work Sampling Methodology

Tools for Application of Work Measurement Data

- Standard Time Systems
- Standard Data Application Procedures
- Synthetic Basic Motion Time Systems
- Tools for Establishing Standards on Indirect Work
- Mathematical and Graphical Procedures for Establishing Time Standards

Methods and Standards Automation

CLASSIFICATION OF SCIENCE AREAS PERTINENT TO INDUSTRIAL ENGINEERING

BASIC SCIENCES

Physics (S.1)
Chemistry (S.2)
Physiology (S.3)

SOCIAL AND BEHAVIORAL SCIENCES

Psychology (S.4)
Sociology (S.5)
Economics (S.6)

ABSTRACT & QUANTITATIVE THOUGHT

Mathematics (S.7)
Probability & Statistics (S.8)
Philosophy (S.9)
Information Science (S.10)
Computing Science (S.11)
Systems Science (S.12)

ENGINEERING SCIENCES (S.13)

Materials Science
Thermodynamics and Heat Transfer
Electrical Sciences
Statics & Strength
Dynamics
Fluid Mechanics

SCIENCES OF ENGINEERING DISCIPLINES (S.14)

Operational and Decision Sciences
(Related to Industrial Engineering)
(Sciences Related to Other Engineering Disciplines Not Listed.)

BASIC SCIENCES

PHYSICS

Electricity and Magnetism

- Electrostatic Fields
- Magnetic Fields
- Induced EMF's
- Maxwell's Equations

Mechanics

- Mechanics of Particles
- Systems of Particles
- Rigid Bodies

Heat

- Thermometry
- Heat Transfer
- Specific Heat
- Laws of Thermodynamics

Sound and Acoustics

Light and Optics

- Geometrical Optics
- Illumination
- Interference
- Diffraction
- Dispersion
- Absorption
- Polarization
- Lasers

Modern Physics

- Nuclear
- Molecular
- Solid State

Table S.2

BASIC SCIENCES

CHEMISTRY

Molecular Structure

Chemical Bonding

BASIC SCIENCES

PHYSIOLOGY

Sensory Processes

Physiology of Exercise

Human Anatomy

- Nervous
- Endocrine
- Respiratory
- Excretory
- Digestive
- Cardiovascular
- Musculo-skeletal
- Reproductive

Metabolism

Nutrition

Toxicology

SOCIAL AND BEHAVIORAL SCIENCES

PSYCHOLOGY

Cognitive Processes

- Thinking
- Problem solving
- Visual imagery
- Attention
- Memory search

Associative Processes

Perception Theories

Mental Information Processing

Learning

Human Motivation

Physiological Psychology

- Split brain theory
- Physiology of stress
- Biofeedback/biorhythm

Personality Dynamics

Aging

Psychological Testing

- Scaling
- Standardization
- Reliability
- Validity

Interpersonal Behavior

Group Behavior

Organization Behavior

Leadership Theories

Persuasion Theory

SOCIAL AND BEHAVIORAL SCIENCES

SOCIOLOGY

Social Stratification Theory

Population Dynamics

Sociology of Work

- Social Order
- Social System
- Work Role Behavior

Small Groups Theory

- Structure
- Order
- Communication
- Bonding
- Task Performance

Complex Organization Theory

- Nature and types of complex organizations
- Structure
- Organizations and Society
- Organizational Changes

Social Foundations of Recreation and Leisure

SOCIAL AND BEHAVIORAL SCIENCES

ECONOMICS

Economics of Social Issues

- Inflation
- Unemployment
- Population
- Environment
- Natural Resources

Urban and Regional Economics

- Land use
- Urban environment
- Industrial development
- Water policy
- Transportation
- Population demographics
- Natural resource base
- Labor base

Econometrics and Input/Output

Economics of Regulation

Theory of the Firm

- The Market
- Total Revenue Function
- Total Cost Function
- Breakeven/Shutdown
- Economies of Mass Production

Microeconomics

- Supply and Demand
- Marginal Analysis
- Competition
- Allocation

Macroeconomics

- National Income
- Employment
- General Price Level
- Consumption
- Investment
- Government Spending and Taxation

Money and Banking

- Bank Structure and Competition
- Federal Reserve System
- Interest Rates
- Employment
- Prices

Finance

- Allocation of Funds
- Asset Management
- Financial Structure
- Policy Determination
- Money and Capital Markets
- Flow of Funds
- Multinational Considerations

Investments

- Stocks, Bonds, Commodities
- Options
- Portfolio Theory

Auditing Theory

ABSTRACT & QUANTITATIVE THOUGHT

MATHEMATICS

Basic Mathematics and Set Theory

Trigonometry

Geometry

Euclidean/Non-Euclidean Geometries

Calculus

- Differential
- Integral
- Vector Analysis
- Series/Sequences

Differential Equations

- Ordinary Differential Equation Theory
- Finite Difference Theory
- Transforms

Linear Algebra

- Linear Spaces
- Linear Transformations
- Matrices
- Systems of Equations

Modern Algebra

Number Theory

- Divisibility of Integers
- Congruences
- Residues
- Primes

Numerical Analysis

- Error Analysis
- Interpolation
- Integration
- Systems of Equations
- Roots of Equations
- Power Series

Combinations

- Counting Techniques
- Recurrence Relations
- Generating Functions

Topology

Calculus of Variations

Graph and Network

Boolean Algebra

Complex Analysis

Fourier Analysis

Convergence Theory

ABSTRACT & QUANTITATIVE THOUGHT

PROBABILITY AND STATISTICS

Basic Probability Theory

Random Variables

- Probability Distributions
- Distribution Functions
- Moments
- Expectation
- Functions of Random Variables
- Transformation of Random Variables
- Covariance
- Chebyshev's Inequality
- Camp-Meidel Inequality
- Law of Large Numbers

Descriptive Statistics

Sampling Theory

- Statistics
- Sampling distributions
- Randomization theory
- Order statistics

Estimation Theory

- Point estimation
- Interval estimation

Hypothesis Testing Theory

- Hypotheses
- Sample size
- Risks
- Goodness of Fit

Design of Experiments

- Design Models
- Hypotheses
- Randomization
- Expected Mean Squares
- Confounding
- Replication
- Response Surface Theory

Analysis of Variance and Covariance

Regression

- Linear
- Multiple
- Correlation
- Transformations
- Prediction
- Confidence Intervals

Stochastic Processes

- Counting Processes
- Stationary Processes
- Birth and Death
- Renewal Theory

Nonparametric Statistics

Bayesian Theory

Spectral Analysis

ABSTRACT & QUANTITATIVE THOUGHT

PHILOSOPHY

Social Values

Critical Thinking

- Correct Reasoning
- Logic and Language
- Argumentation
- Detection of Fallacies

Principles of Symbolic Logic

- Symbolic Analysis
- Calculus of Propositions
- Nature of Axiom Systems

Philosophy & the Quality of Life

Ethics

- Moral Judgments
- Moral Value
- Relativity & Objectivity
- Freedom and Responsibility

Social Philosophy

- Social Authority
- Human Rights
- Political Forms

Ethical Issues in Technology

- Genetic Engineering
- Human Experimentation
- System Design
- Product & Service Design
- Resource Utilization

Scientific Method

ABSTRACT & QUANTITATIVE THOUGHT

INFORMATION SCIENCE

Data Encoding and Decoding

Data Processing Logic

- Sorting
- Searching
- Merging
- Manipulation
- Updating
- Graph Processing

Data Structures

- Linked Lists
- Strings
- Graphs
- Trees

Integrated Information System Concept

Information Theory

Decision Support Systems Concepts

ABSTRACT & QUANTITATIVE THOUGHT

COMPUTING SCIENCE

Computer Organization

- Memory, Central & Auxilliary
- Processor; Single, Multi
- Input/Output
- Registers, Counters, Buffers

Auxilliary Storage Devices

Virtual Storage

Computer Operation Control

- JCL - Job Control Language
- OS - Operating Systems
- Editors

Teleprocessing

Remote Computing

Real Time

Time Sharing/Multi-Programming

Distributed Computing Concepts

Computer Networking Concepts

Computer Programming Fundamentals

- Arithmetic Operations
- Looping
- Branching (Logic Comparison)
- Sub-program Linkage
- Addressing Techniques
- Input/Output Operations
- Program Structuring
- Binary Arithmetic
- Parity Methods

Computer Languages

- Machine Language
- Compilers
- Assemblers, Interpretors, Translators
- High Level Languages

File Address/Security

- Multi-key Files

File Access Concepts

- Sequential
- Direct
- Indexed
- Tree Structured
- Inverted Files

Data Structure Concepts

- Stacks
- Queues
- List Structures
- Sparse Matrices

Text Processing Concepts

Computer Graphics

Computer Arithmetic and Rounding Errors Concepts

Theory for Numeric Algorithms

Theory of Non-Numeric Algorithms

Computability

- Time
- Core Requirements

Microcomputer Concepts

Analog Computer Concepts

ABSTRACT & QUANTITATIVE THOUGHT

SYSTEMS SCIENCE

Total Systems Concept

Mathematical Systems Theory

- Concepts of a General System
- Open and Closed Systems
- System Structure
- Decomposition and System State
- Attributes & Behavior of Systems
- Reproducibility and Controllability
- Goal-Seeking Behavior

Feedback Control Theory

- Models of Control Systems
- Control System Characteristics
- Performance of Control Systems
- Stability

Adaptive Control Processes

- System Identification
- The Decision Problem
- The Modification Problem
- Pattern Recognition

Large-scale Systems Theory

ENGINEERING SCIENCES

Material Science

Crystallography

Polymerization

Iron-Carbon System

Properties of Materials

- Hardness
- Malleability/Ductility
- Conductivity
- Viscosity
- Magnetism
- Porosity
- Strength
- Brittleness
- Density
- Melting Point
- Resistance to Corrosion

Elastic/Plastic Deformation

Fatigue

Strengthening Mechanism

Thermodynamics and Heat Transfer

Work and Heat

First Law of Thermodynamics

Second Law of Thermodynamics

- Heat Engines
- Refrigerators (Heat Pump)
- Thermal Efficiency
- Coefficient of Performance

Entrophy

Basic Concepts of Heat Transfer

- Convection, Conduction, Radiation
- Analysis of Heat Exchangers

Electrical Sciences

Basic Circuit Concepts

- Ohm's Law
- Kirchoff's Laws
- Single Loop, Single Node Circuits
- Resistor Combinations
- Voltage and Current Division

Circuit Analysis

- Node Analysis
- Mesh Analysis
- Linearity and Superposition
- Thevenin and Norton Equivalents

Energy Storage and Phasors

- Inductor
- Capcitor
- R, L, C Combination
- Impedance and Admittance

Statics

Vector Quantities

Equilibrium

Distributed Forces

Mechanics of Deformable Bodies

Axial Loadings

Torsion

Bending

Combined Loading

Buckling

Dynamics

Kinematics (motion without reference to force) of Particles

Kinetics (motion with reference to force) of Particles

Plane Kinematics of Rigid Bodies

Plane Kinetics of Rigid Bodies

Fluid Mechanics

Fluid Statics

Concepts of Fluid Mechanics

The Conservation Equations

Ideal Fluid Flow-Bernoulli Equations

Fluid Flow

SCIENCES OF ENGINEERING DISCIPLINES

OPERATIONAL AND DECISION SCIENCES

(Science Base Originating from Industrial Engineering)

Work Sciences

Rate of Work (Pacing)

Duration/Fatigue/Rest

Quantity of Work

Mental Acuity

Efficiency

Responses to:

- Reward Structure
- Work Environment
- Authority/Responsibility Relationships

Worker Learning

Time Measurement

Motion Economy

Human Factors/Ergonomics

Information Input

- Visual/Auditory/Tactual Displays
- Speech Communication
- Encoding (Sensing)

Information Processing and Decisions

- Interpretation
- Response
- Human Control

Physical Output

- Human Motor Response
- Controls, Tools, Related Devices

Work Space and Arrangement

- Anthropometry
- Spatial Relations

Work Environment

- Illumination
- Atmospheric Conditions
- Noise
- Effects of Human Motion
- Environment Dimensions
- Safety and Hygiene

<u>Engineering Economy</u>

Economic Exchange

Time Value of Money

Effects of Inflation

Return on Investment

Break-Even Concept

Cost Accounting Principles

Cash Flow Principles

Principles of Compounding

Equivalence Concepts

Definition of Alternatives

Planning Horizon Concept

Depreciation/Depletion

Taxation

Cost/Benefit Theory

Risk/Uncertainty Theory

<u>Decision Theory</u>

The Basic Decision Problem

Decisions Under Assumed Certainty/Risk/Uncertainty

Set of Alternative Decisions

Set of States of Nature

Set of Potential Experiments

Sets of Outcomes of Potential Experiments

Utility Function

Choice of Optimization Principle

Set of Weights (Probabilities)

Modes of Analysis

- Normal Form
- Extensive Form (Terminal & Preposterior Analysis)

Multiple Objective Criteria

Bidding Theory

Game Theory

Group Decision Making

<u>Assurance Sciences</u>

Design Review Concepts

- Specifications and Tolerances
- Performance Criteria
- Producibility/Inspectibility
- Safety
- Reliability
- Maintainability
- Availability

Quality Program/System Concepts

- Basic Concepts of Quality Assurance
- Quality Costs
- Calibration and Measurement (Metrology)
- Inspection and Measurement Error
- Traceability of Components
- Process Control
- Process Capability to Meet Specifications
- Acceptance Sampling

Materials Processing Sciences

Shape Change

Machining

- Chip Removal
- Non-Traditional

Finishing

Joining

Changing Physical Properties

Productive Work Systems

Prinicples of Facility Location & Layout

- Material & Information Flow
- Relationships
- Performance Criteria

Principles of Manufacturing Systems

- Product and Process Documentation
- Operation Sequencing & Assembly Line Balancing
- Standard Manufacturing Times
- Throughput Rate Analysis
- Capacity Analysis
- Equipment Sizing
- Human/Machine Interface
- Equipment Selection
- Transfer Devices and Material Handling
- Buffers
- Inspection and Test
- Packaging
- Storage
- Information Linkages
- Automation
- Computer/Numerical Control
- Robotics
- CAD/CAM/CAT

Principles of Service Systems

- Service and Process Documentation
- Operation Sequencing and Work Balancing
- Standard Service Time
- Throughput Rate Analysis
- Capacity Analysis
- Equipment Sizing

Human/Equipment Interface
Equipment Selection
Transfer Devices and Material Handling
Buffers
Inspection and Test
Packaging
Storage
Information Linkages
Automation
Computer Control
Robotics
CAD/CAS/CAT

<u>Operation Planning and Control</u>

Specification of Planning Horizon

Demand Forecasting

Operations Planning

Time Phased Product Quantities
Time Phased Component Quantities
Time Phased Equipment/Facilities Requirements
Time Phased Labor Requirements
Consolidated Operations Plan

Inventory Planning and Control

Materials Requirement Planning
Inventory Control Principles

Operations Scheduling

Facility Loading
Workload Evaluation
Task Sequencing (Decision Rules)
Consolidation of Detailed Schedule

Dispatching and Progress Control

Production Initialization
Operational Data Acquisition
Performance Evaluation
Short-Term Corrective Action
Long-Term Corrective Action

Operations Research

Mathematical Programming

- Linear Programming
- Non-Linear Programming
- Goal/Multi-Objective Programming
- Stochastic Programming
- Integer/Mixed Integer Programming
- Dynamic Programming
- Parametric/Sensitivity

Queueing Theory

Markovian Processes

Inventory Theory

Simulation

Network/Flow Theory

Reliability

Quality Control

Monte Carlo Theory

Optimization Theory

- Classical
- Search
- Heuristics

Variance Reduction

HUMAN INTERACTION WITH COMPLEX SYSTEMS:

A RESEARCH PROSPECTUS*

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INTRODUCTION

Systems are becoming increasingly complex. The driving forces include desires and/or requirements to reduce risk, pollution, and energy consumption as well as objectives of increased productivity and performance. The primary enabling forces are trends in computer technology.

Humans interact with these systems in many ways. The roles of humans include designer, fabricator, manager, operator, maintainer, and user. In all of these roles, increased system complexity presents difficulties for humans. This paper suggests that understanding and ameliorating these difficulties should be one of the major items on the research agenda.

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*Position paper prepared for National Science Foundation Workshop on Research Directions in Industrial Engineering, Atlanta, May 1982.

POSSIBILITIES OF AUTOMATION

While most observers agree that there is ample evidence upon which to base the conclusion that human interaction with complex systems can lead to problems (e.g., Three Mile Island accident, DC-10 crash in Chicago, and false alarms in the air defense system), many feel that this situation is temporary. The basis for this feeling is the premise that humans, at least as operators and maintainers, will eventually be totally replaced by automation and, as a result, the plague of "human error" will disappear. Given this perspective, one would naturally advocate placing highest priority on research in automation and perhaps optimization.

As promising as this point of view may seem, it is too narrow to succeed. One reason is that humans are not replaced by automation; they are shifted to new roles, typically roles which involve dealing with increased complexity. Thus, for example, sophisticated computer-based systems that can almost replace the aircraft pilot result in tremendous increases in the complexity of maintenance problems. Perhaps more obviously, replacing the elevator operator with an automatic system resulted in more complex maintenance problems.

Of course, to eliminate both the operator and maintainer, one must be sure that the designer has anticipated all possible contingencies as well as all possible combinations of contingencies. This places quite a burden on the designer and will inevitably result in human error, in this case on the part of the designer rather than the operator or maintainer. The only way to avoid human error completely is to avoid having humans involved with complex systems, which requires that systems design other systems to be managed, operated, and maintained by other systems and used by other systems in a manner that has absolutely no impact on humans. Obviously, such human-less systems would be pointless.

Thus, human-system interaction, at least at some level, is a permanent condition and the effects of increased complexity on this interaction is, therefore, a problem of lasting interest for which an appropriate research base should be built. To do this, it is important that the appropriate research questions be asked. The remainder of this paper suggests what the nature of these questions should be.

THE IMPORTANT QUESTIONS

At least fifty years has been devoted to gaining an understanding of how people and systems should interact. Almost all of the earlier work and much of the current work in this area has emphasized the physical aspects of human-system interaction. The questions asked concerned whether or not humans could physically fit in the system, see their displays, reach their controls, and feel comfortable, or at least survive, in the system's environment. These questions certainly will remain important. However, they are not the crucial questions with regard to humans interacting with increasingly complex systems.

It seems to this author that there are three questions of particular importance. First, within any specific domain, how ought one go about determining which tasks _should_ be performed by humans and which tasks _should_ be performed by computers? This is a very different question than that of which tasks _can_ be performed by humans and which tasks _can_ be performed by computers. Progress in computer science has resulted in computer programs that, within somewhat limited domains, can make decisions and solve problems with performance comparable to, or sometimes better than, human experts. Of course, these programs are, by no means, able to completely replace the human experts in question (e.g., doctors) because the human designers of these programs are not confident (nor are the doctors) that all contingencies and combinations of contingencies have been accounted for. Nevertheless, the computer's capabilities have evolved to the extent that they are significantly overlapping with those of humans.

Why not use computers to the extent possible and have humans perform all of the tasks that have not yet been automated? Thus, for example, computers would handle all of the straightforward diagnostic problems and humans would deal with the difficult problems. As computer capabilities continue to evolve, more and more tasks would become straightforward and all that would remain for humans would be the very infrequent, very difficult tasks. The role of humans would then be to take over occasionally (once per month, year, or decade?) and cope with levels of complexity that computers could not manage. But, with little or no practice, would humans be able to cope? Or, would the problem solving skills of the humans involved be atrophied?

It is quite possible that humans should have responsibility for some tasks that could be automated but should not be in order to maintain humans' skills to react appropriately when the automation fails or encounters a situation for which it was not designed. There is an obvious tradeoff here. Unlike their ancestors, most humans do not have the skills to survive in the wilderness; however, it unlikely such skills will ever be necessary in the modern world. Similarly, the operation and maintenance of many systems once required manual skills, particularly strength, that are no longer necessary and unlikely to ever again be necessary. It would be a poor investment to concentrate on maintaining these types of manual skill.

However, there are some types of human skill that, hopefully, will never become obsolete. These are in the areas of decision making and problem solving. Humans' abilities in these areas must be maintained. The important question here involves identifying the nature of these skills and determining how the allocation of tasks among humans and computers affects the retention of human decision making and problem solving abilities.

Assuming that the above question can be resolved, the obvious result will be that some tasks will be automated and others will not. For those tasks that are automated, a new question arises. Based on the premise that no automation will be completely fail safe, what will humans need to know in order to detect abnormalities that the automation cannot handle, diagnose their sources, and compensate appropriately? Is it necessary that humans understand "how the system works" or is it sufficient that they only know "how to work the system"? It is quite likely that some level of knowledge between these two extremes is the most appropriate. Should this knowledge be gained during training or can aiding schemes be devised that will enable humans to access this information only when it becomes necessary?

One approach to resolving the issues surrounding this question is to design systems such that they automatically shut down if the automation fails or, alternatively, such that they shut down if the symptoms of the failure (i.e., deviations of important variables) exceed the bounds of some safety envelope. Within this envelope, humans are free to attempt to keep the system operating by utilizing both formal and informal procedures and, if necessary, innovating to diagnose and/or compensate for the abnormality. Training and aiding of humans in problem solving situations where they must innovate is an area of study that has only recently emerged.

The third important question involves those tasks that are not automated, either because that cannot be or should not be automated. As might be imagined from the foregoing discussion, it is this author's opinion that these tasks will emphasize decision making and problem solving. From this perspective, systems should be designed to take advantage of humans' cognitive abilities to recognize and classify a wide variety of patterns and cope with ambiguous situations, and also designed to help humans to overcome their cognitive limitations such as short-term memory contraints, inherent biases, and adoption of inappropriate heuristics.

The important question in this area involves identifying the cognitive abilities and limitations that have most impact on human interaction with complex systems, particularly in terms of how these abilities and limitations are affected by increased complexity. Once this has been accomplished, the question then becomes one of determining appropriate training methods and aiding schemes for exploiting abilities and overcoming limitations.

DISCUSSIONS AND CONCLUSIONS

To summarize, the three important questions outlined above are:

1. How should tasks be allocated among humans and computers to assure an appropriate tradeoff between short-term system performance and long-term retention of human decision making and problem solving skills?

2. What level of understanding should humans have in order to be able to detect complex abnormalities that computers have not been programmed to handle, diagnose the sources of the abnormalities, and compensate for their effects?

3. What types of training and aiding are appropriate for helping humans to best utilize their cognitive abilities and also overcome their cognitive limitations when interacting with complex systems?

Some aspects of these questions are new; some aspects involve issues that psychologists have studied for decades. Progress in psychology will not, however, eventually yield answers to the above questions. Neither will a purely disciplinary engineering approach be adequate. A broader perspective is needed.

Since the types of problem alluded to in this paper all involve complex engineering systems (e.g., aircraft, ships, utility and manufacturing plants, transportation and commnuication networks), these questions should be addressed from a point of view that considers the many behavioral and technical relationships that affect the abilities of these complex systems to achieve the objectives for which they were designed. This requires studying real systems in their entirety or close approximations to them. It also necessitates studying real managers, operators, maintainers, etc. Finally, it involves integrating knowledge (both facts and methodologies) from a wide variety of disciplines in order to gain a balanced perspective for the overall problem.

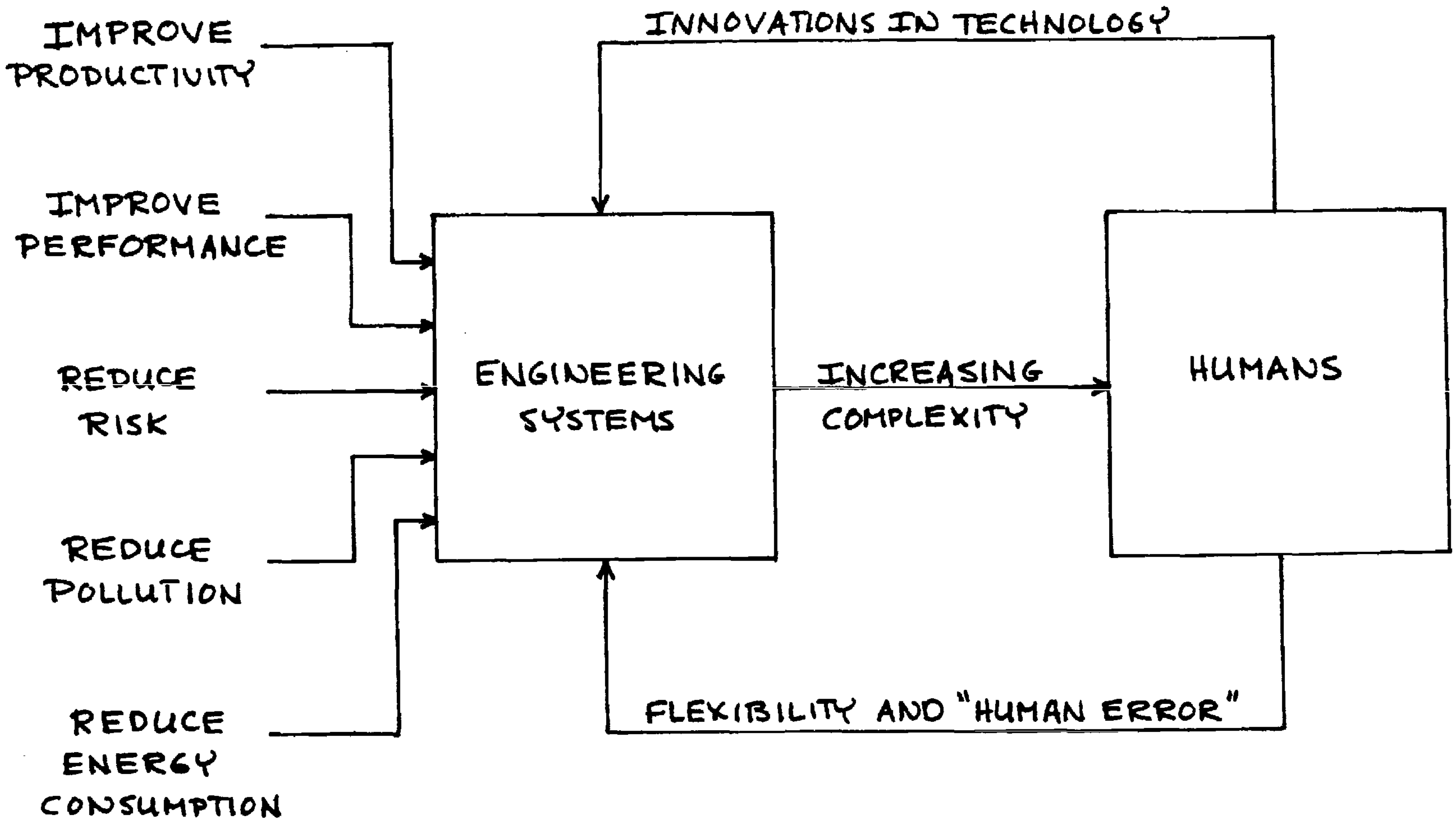
Unfortunately, universities appear to find it very difficult to develop and maintain coordinated assaults on realistically complex problems. This is partially due to the intense disciplinarity of most university programs where often faculty are not encouraged, and graduate students are not allowed, to transcend the confines of their disciplines. A further difficulty is the universities' penchant for producing narrow facts rather than broad design concepts and their inclination toward optimization algorithms rather than problem solving methodologies.

Nevertheless, the universities have the intellectual resources which, if properly motivated and organized, have the potential for making substantial contributions to the solution of emerging problems associated with complex systems. This motivation and organization is, however, unlikely to come from within. Sources of funding are obviously needed. Equally necessary is a constituency with a vested interest in having the problems of concern solved. These needs suggest that an appropriate mechanism might involve government, industry, and academia. Perhaps government should provide seed money, industry should invest development and implementation funding, and academia should commit itself to solving realistically complex problems.

Few would argue against the premise that our technological society is becoming increasingly complex. Many see automation as the solution. However, the key to coping with complexity lies in the recognition that solutions must be designed, implemented, and monitored by humans. Thus, human interaction with complex systems is both the problem and the solution. The central challenge is to pursue research that will provide the understanding necessary to answer the questions posed in this paper. These questions are crucial since the true test of a technological society is not its ability to build complex systems; it is its ability to manage, operate, and maintain them.

HUMAN INTERACTION WITH COMPLEX SYSTEMS

WILLIAM B. ROUSE



IMPROVE PRODUCTIVITY
IMPROVE PERFORMANCE
REDUCE RISK
REDUCE POLLUTION
REDUCE ENERGY CONSUMPTION
ENGINEERING SYSTEMS
INNOVATIONS IN TECHNOLOGY
INCREASING COMPLEXITY
HUMANS
FLEXIBILITY AND "HUMAN ERROR"

TRADITIONAL QUESTIONS

CAN HUMANS:

1. PHYSICALLY FIT IN THE SYSTEM?
2. SEE THEIR DISPLAYS?
3. REACH THEIR CONTROLS?
4. FEEL COMFORTABLE IN THE ENVIRONMENT?

NEW QUESTION NUMBER ONE

HOW SHOULD TASKS BE ALLOCATED AMONG HUMANS AND COMPUTERS TO ASSURE AN APPROPRIATE TRADEOFF BETWEEN SHORT-TERM SYSTEM PERFORMANCE AND LONG-TERM RETENTION OF HUMAN DECISION MAKING AND PROBLEM SOLVING SKILLS?

NEW QUESTION NUMBER TWO

WHAT LEVEL OF UNDERSTANDING SHOULD HUMANS HAVE IN ORDER TO BE ABLE TO DETECT COMPLEX ABNORMALITIES THAT COMPUTERS HAVE NOT BEEN PROGRAMMED TO HANDLE, DIAGNOSE THE SOURCES OF THE ABNORMALITIES, AND COMPENSATE FOR THEIR EFFECTS?

NEW QUESTION NUMBER THREE

WHAT TYPES OF TRAINING AND AIDING ARE APPROPRIATE FOR HELPING HUMANS TO BEST UTILIZE THEIR COGNITIVE ABILITIES AND ALSO OVERCOME THEIR COGNITIVE LIMITATIONS WHEN INTERACTING WITH COMPLEX SYSTEMS?

SPECIFICATIONS OF AN APPROACH

1. CONSIDER REAL SYSTEMS IN THEIR ENTIRETY

2. STUDY ACTUAL MANAGERS, OPERATORS, MAINTAINERS, ETC.

3. INTEGRATE KNOWLEDGE FROM MANY DISCIPLINES

4. INVOLVE INDUSTRY, ACADEMIA, AND GOVERNMENT

The Industrial Engineer's Role in Manufacturing Systems Research*

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NSF/IIE Workshop
on
Research Directions in Industrial Engineering

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* This paper draws heavily on material presented in "Current and Future Roles of IE in CAD/CAM" by A. B. Bishop and R. A. Miller, a modified version of which was published in Industrial Engineering, Volume 13, Number 11, November, 1981, under the title "CAD/CAM and the Role of the Industrial Engineer."

I. Introduction

To define and assess the roles of Industrial Engineers in production research in general and manufacturing systems research in particular, we must examine the areas of interest and expertise of the IE and match these with the functions which must be performed to design and operate manufacturing systems. Therefore, we first describe these areas of IE interest as represented in the instructional and research programs in Industrial-Engineering related departments in American universities. Then, because of the transcendent influence of computer technology on every facet of a manufacturing system, a brief discussion is presented of the ways in which the computer can and must be used in this context. This includes the traditional uses of the computer as a component of an operating system and as a computational tool and of its emerging, though far from fully developed, use in a partnership role with the engineer and operator as a member of the manufacturing team. We then define the functional components which comprise a manufacturing system, their structural interrelationships, and the computer's use in accomplishing each. Finally the role of the IE in the functioning of each of these component areas and of the manufacturing system as a whole is addressed. Our conclusion is that the IE has a central leadership role to perform plus some unique responsibilities relative to the acceptability and effectiveness of our nation's production system.

II. The Faces of Industrial Engineering

If industrial engineering were to be defined by what industrial engineers do in the pursuit of their occupations, there might well be as many definitions as IE's. Although the Institute of Industrial Engineers has adopted an official, though somewhat lengthy, definition, the tremendous diversity of IE interests, responsibilities, tasks, and talents makes formal definition difficult and at best tenuous. Examination of programs in IE departments in American universities, however, indicates that many are described in terms of four interrelated tracks or areas of interest and concern. In some cases, these four are stated explicitly as options within the program. Although the specific titles used may vary, these areas are:

1. Management Systems,
2. Man-Machine Systems,
3. Manufacturing Systems, and
4. Operations Research.

There is considerable evidence to indicate that over the years these particular titles have been proven both robust and essentially all inclusive.

Since all of these areas of concern are also shared by people in other disciplines it is necessary to differentiate the explicit roles and involvement of the IE from the managers, psychologists, manufacturers, mathematicians, and others interested in these areas. First, like all engineers, the IE is responsible for the design of products and systems to fill the needs of society. The IE's primary area of responsibility and concern has been the design of production systems, including the design of the managerial and operating functions of these systems. Furthermore, they have been doing their tasks well enough so that today they are being asked to broaden their areas of attention to a wide variety of operating and service activities outside of the production area. In almost all cases, however, their emphasis is still on systems synthesis.

Second, industrial engineering responsibilities for systems design also extend beyond those of most engineers in two ways. One is the necessity to effectively integrate human beings into the systems they design. People have many capabilities, particularly in cognitive areas, that machines do not have, so are indispensible in production-system design and operation. Hence, knowledge of human behavior and performance is essential for IE's. The other is the emphasis on economic considerations in the design and operation of production systems. Very simply, these systems must produce products which can be sold at a profit in accessible markets. Therefore, it is not sufficient to merely develop some system that will produce a desired product; the system must be capable of producing the product at a profit.

The implications of these two factors are far-reaching and significant. As almost the sole source of interest among engineers in the role of humans in integrated systems, the IE must maintain a strong concern for what humans can do best, what machines can do best, and what computers can do best. A manufacturing system designed with these types of considerations in mind will look considerably different, should operate much more effectively, and should result in a much higher quality of life for all involved than a system designed with the primary objectives of replacing people with robots and turning full control over to the computers. Complete functional analyses of tasks and capabilities are required for computer and robot assisted systems to work efficiently and to be accepted by the labor force and society in general. The importance of the economic considerations increases every day, particularly with the current state of our economy. High quality products produced at a profit are essential to reverse the current downward trend in the annual productivity of American industry and to help it regain its competitive position and market share.

In summary, the IE by background, experience, and motivation has much to offer in the area of manufacturing systems and to perform meaningful research in their planning, design, and operation. A detailed discussion of needed IE contributions will be considered in Section V of this paper where it is shown that manufacturing systems provides a natural and vital focal point for all phases of industrial engineering interest and concern.

III. Computer Functions

The computer has traditionally been viewed in each of two ways:

1. as a component of an operating system, and
2. as a computational tool.

The computer is viewed as a system component whenever it is designed into an operating system. Its functions include the storage, organization, and retrieval of data, and real-time control wherein each task is clearly defined and structured when the system is set up. Examples of the use of the computer in this "bookkeeping" mode involve company payrolls, bank accounts, airline reservations, inventory and process control, vendor audits, and standards maintenance. As a computational device to solve problems involving quantitative data, the computer is basically a "number cruncher." Usually the emphasis is on planning, design, and research activities such as plant layouts, process-capability studies, resource allocation, production scheduling and sequencing, and calculation of minimum-cost preventive maintenance schedules. Most such cases involve numerical solutions to complex functional equations, as in queuing systems, or optimum-seeking algorithms based on simplex manipulations or branch-and-bound techniques.

The current state of computer technology now demands a third view of the computer if the full benefits potentially available from computer aiding in design and manufacturing functions are to be realized. Specifically, it is essential for today's engineer and all concerned with computer-assisted man-machine systems to view the computer as a partner. The partnership idea refers to a kind of symbiosis between human and machine in which knowledge, concepts, and responsibilities are shared. Both engineers and operators must know the appropriate things about computers and computers must be designed and programmed to work together with humans. This is distinct from the component idea where the computer is used for specific, predefined tasks at the direction of humans. People and computers do different things well and the problem is to get them to work together in a natural, empathetic way. This implies that questions (problems) such as alienation, maintaining a sense of human dignity and worth, trust, and certainly others must be considered for humans to accept and hence interact with the computer as a partner in the industrial and everyday world. This effectively makes the computer a member of the planning, design, and management teams, working with the engineer to plan and design and with the engineer and operator to keep the production system operating in spite of machine breakdowns, new orders, material variations, personnel problems, and cost changes. The latter requires that the computer operate one-line for real-time decision-making.

In summary, objectives proposed for computerized manufacturing systems go beyond the current component and computation stages, and there are many technical, psychological, and sociological barriers which must be understood and overcome before the partnership stage is reached. Further, the fulfillment of the hoped for contributions of our manufacturing systems will not be fully met unless this occurs.

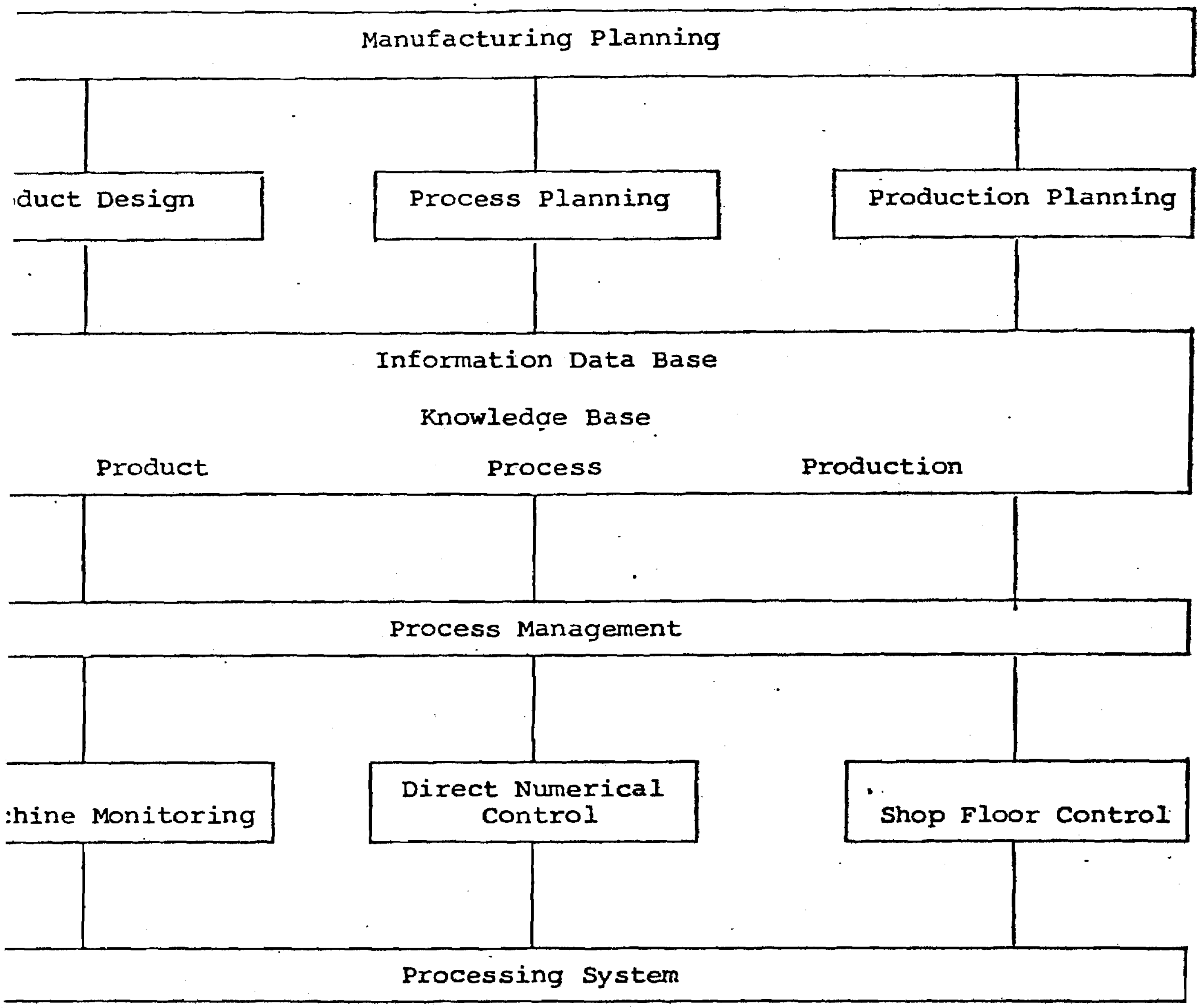
IV. Computer-Aided Manufacturing Systems

A truly integrated manufacturing system can be described in terms of the functions that must be performed to produce products and by the interrelationships among these functions. These include the planning, design, operation, and management of the manufacturing facilities and the design of the product.

A computer-aided manufacturing system is thus a manufacturing system in which current computer technology is incorporated as most appropriate in each of the component functions. It thus includes in their entirety those activities commonly called CAD, CAM, CAT and the general aspects of computer-aided engineering. The partnership role of the computer discussed in the previous section is so vital here that we could well define the computer-aided manufacturing system as the exploiting of this partnership role in these design and manufacturing areas. We, therefore, must determine how best to use the computer's tremendous memory, calculating ability, and reliability in combination with the human's inherent reasoning and cognitive capabilities to obtain optimal system performance. Figure 1 represents in generalized form the structure of an integrated manufacturing system.

The planning and design functions are located at the top of the figure. Note that they include the product, the process, and the overall production system. Full realization of the benefits inherent in manufacturing systems technology requires that these planning functions be systematically coordinated so that the interrelationships among the components can be explicitly studied and accounted for in the total system design. Product Design utilizes the computer, heavily augmented with interactive graphics, in both its bookkeeping and number-manipulation roles. It involves the aesthetic features of the product, the mating among parts, and structural analysis, usually based on finite-element approaches. Computer-Aided Design is commonly defined specifically as the performance of these product-design tasks with computer assistance. This function is traditionally performed by mechanical engineers. Process Planning, the result of which is the process design, primarily places extensive number-crunching requirements on the computer. The same is true with overall Production Planning, which includes the design and integration of control, operating, and support activities with the process. Both areas are involved with resource-allocation decisions and the optimization of facilities design and control. As interactive graphics gains acceptance in such areas as plant layout and the design of production and inventory control systems, the computer's bookkeeping role will grow.

Figure 1



Manufacturing Planning
duct Design
Process Planning
Production Planning
Information Data Base
Knowledge Base
Product
Process
Production
Process Management
:hine Monitoring
Direct Numerical Control
Shop Floor Control
Processing System

The implementation of plans and the embodiment of designs into an operating manufacturing system require both an information base, commonly referred to as a data base, and a knowledge base. It is important that we be aware of the difference between the two. Data bases can currently be dealt with automatically. The semantic component or content is always externally defined, i.e., what a given data item means is established external to the data base, generally through conventions and constraints set up by the designer of the data base. As such, a data base becomes a representation of selected information. A knowledge base, however, is the structure which gives information its meaning. It is what we draw on when interpreting data, solving problems, making judgments, and the like. Our knowledge bases cover an almost limitless range, including factual knowledge regarding materials and processes, both analytic and analogue reasoning abilities, and numerous relationships drawn from our experience (e.g., operators of processes know many things about the process that the designer does not).

The point is that the wide scale integration of design and manufacturing envisioned in CAD/CAM and hence in integrated computer-aided manufacturing systems depends on the presence of such knowledge bases suitable for use by a computer. Unfortunately this is not generally possible at present, and the consequence can be premature standardization which limits the domain of the problems addressed to conform to whatever restricted knowledge base might be available. A more risky but very necessary approach would be to place few constraints early, develop the partnership roles by letting the computer and human do what each does well and try to understand the process better before providing limited technical solutions. In summary, it must be emphasized that an adequate data base and knowledge base must be available to relieve the necessity for handling planning and design data external to the computer system and thus permit full integration throughout the system, particularly

(1) between the product-design stages and (2) between all the planning and design stages and the operating stages.

On-line, real-time management functions are needed to operate the production system in a productive manner. Computers in partnership roles are essential for all such functions. Machine Monitoring, which involves the programming of machine operations, the automatic gauging of output, and feedback control, is used to assure that the machine is doing its intended job. Unfortunately, many people incorrectly and shortsightedly consider machine monitoring as the entirety of computer aiding in manufacturing systems, a view which could drastically limit the success or even doom to failure efforts to improve manufacturing productivity. Direct Numerical Control, places the computer in a supervisory role over one or more CNC machines. The supervisory computer provides programs to the individual CNC machines according to some plan or based on new real-time data. DNC thus requires a knowledge of hierarchial systems of computers and the tasks of vertical integration between levels. Shop Floor Control is the management of the over-all production system. It involves real-time responses to system perturbations in terms of changes in production scheduling, manpower-loading, routing, inventories, tooling, and scrap and rework control activities, all of which are traditional areas of IE involvement. The challenge of computer-aided manufacturing systems, however, is to perform these functions on-line either automatically by computer or with an interactive system involving the computer and the engineer or operator.

V. The Role of the Industrial Engineer in Manufacturing Systems R and D

Our quick analysis of the structure of manufacturing systems reveals one of the most comprehensive and complex systems with which engineers have ever had to deal. Full realization of the benefits potentially available from the huge capital investments in computer-aided manufacturing systems thus requires innovative, sound, effective systems design and engineering. Except for the Chemical Engineer, whose systems expertise is usually limited to chemical processes, the IE stands alone among engineers in his commitment and experience with production systems. Those IE's who have been serious about developing themselves as systems engineers thus have a central role to play in these efforts.

Since less than five percent of the time a workpiece spends in a production system is involved in direct processing operations such as milling or turning, explicit attention must also be given to its positioning, loading, gaging, and movement. Sequencing and scheduling are also of vital importance for efficient machine utilization and assembly. In addition, flexible manufacturing facilities such as programmable group-technology cells are almost essential for the 75% of manufacturing operations not done on production lines. There is thus a great need for the effective performance of the traditional IE functions of facilities design, production planning and control, materials handling, and work design. The IE must continue to be involved in these areas, but with an expanded area of involvement.

Computer technology is making possible (1) the elimination of unsafe and unpleasant jobs, (2) higher quality and faster performance of many intermediate-skill-level jobs, and (3) the creation of new, potentially more enriched, routine jobs. Therefore, integration of the human into highly computerized production systems actually places increasing emphasis on job analysis and work design. As this occurs, current approaches to this long-standing area of IE responsibility will have to be substantially expanded and updated with new knowledge concerning the human/computer interface. There is much still to be learned about the health and safety of video display monitors. There is also much to be learned concerning optimal systems and procedures for communication and information exchange between humans and computers, particularly with respect to the use of interactive computer graphics. These are vital roles which must be performed by human-factors engineers.

Current experience with automated processes and systems has demonstrated a need for new approaches in labor/management relations. The IE, with his unique combination of technical and engineering-management knowledge, is in an excellent position to help in the development of appropriate procedures and communication channels to enhance the evolvement of productive relationships. This may require some broadening for those IE's who have not previously worked directly in this interface area, but constructive, balanced results require IE involvement.

The tremendous capital investment necessary for integrated manufacturing systems places added importance on sound engineering-economic analysis, a task IE's have engaged in with considerable success for many years. IE's are on average better at this than other engineers and certainly better than traditional accountants, so must be active in this area. Their major challenges, however, will be developing approaches to costing out the layoff and/or re-training of personnel displaced by computerized systems and robots and accounting for the inherent value of the flexibility of a flexible manufacturing system.

The ever-present real-time aspects of manufacturing system operation place considerable emphasis on process-control and shop-floor management optimization algorithms that work in real time. This is an exciting area for the OR-oriented IE, and one which must be handled well. Although some reorientation to real-time decision-making would be required, IE's are in general way ahead of other engineers in their involvement in such matters.

Currently, the biggest obstacle in the development of the majority of computer-aided manufacturing systems is the lack of an adequate knowledge base (see Figure 1). System designers must learn how to accommodate qualitative and judgmental factors in areas such as process planning and scheduling. As stated previously, we have much to learn about the partnership relationships between the engineer and the computer, about the operator and the computer, and about how to put together systems which make maximum use of human knowledge and computer reliability. We also simply do not know enough about the anatomy of such operations as metal cutting and forming, paper formation, plastic flow, and assembly to design the needed adaptive optimal control devices and procedures. Where analytic models are lacking, we must learn to formulate and utilize empirical models in real time and perhaps develop expertise for performing interactive process planning. Considerable basic research is required to fill these voids and the IE will have to take the lead in this effort. His role here will usually be one of motivator, coordinator, and facilitator for the scientists and engineers who specialize in the areas and processes involved, although some direct expertise is available in the industrial engineering community.

Perhaps the most important area in which IE's will have to assume major responsibility will be the engineering of the integration of CAD and CAM and the leadership for the overall synthesis of the manufacturing system. This is because, first of all, this integration is a systems engineering task. It also involves all of the many IE functions, both traditional and extended, outlined above. Finally, the author's personal experience indicates that other engineers show little interest in this integration task. In general, mechanical and other design engineers seem much more intent upon the continued perfection of the Product Design, i.e., CAD, function as an end in itself and content to leave the development of the rest of the system to others. Yet someone must assure that the CAD system does not constrain the design to the point that creativity is impaired or imposes uneconomical requirements on the manufacturing portion of the system. Similarly, the manufacturing engineer, though somewhat more systems oriented, seems to concentrate primarily on Process Planning and Design, Machine Monitoring, and Direct Numerical Control. Thus, the IE has to be the one to carry out the overall system integration, including the CAD/CAM interface.

VI. Conclusion

In summary, IE's have the background, experience, interest, and ability to assume a central position in manufacturing systems research, development, and implementation. Current IE roles emphasize systems engineering, knowledge-base build-up, and overall motivation and leadership. All phases of IE, traditional, management, man-machine/human factors, manufacturing, and operations research, are required. The future will add the additional roles of continuing development, monitoring, evaluation, and, as needed, redirection. We must not be so naive as to think that our first efforts will be optimal, or perhaps, in some cases even effective. The considerable reshaping and updating of IE educational programs necessary for fulfillment of these tasks is already beginning in many departments.

One way or another, however, the tasks outlined above must be accomplished for the sake of the nation's future. In particular, work must specifically be directed to build up the manufacturing system's knowledge base, currently the weakest link in the system, and to the development of balanced, truly integrated systems.

OPPORTUNITIES FOR IE RESEARCH IN MANUFACTURING

James J. Solberg
Purdue University
April, 1982

Prepared for NSF Workshop, Atlanta
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Introduction

The general public has only recently awakened to the realization that there are serious problems in the manufacturing sector of the U.S. economy. Up until two or three years ago, it was widely assumed that, aside from isolated difficulties in certain areas, our industry was the most advanced in the world. Certainly the ordinary man in the street paid little attention to manufacturing, and the same could be said even of the upper management of the companies. For almost thirty years--an entire generation--the major emphasis of American business was on capturing markets in an expanding economy, with little attention paid to the production operations. Although the workers and middle managers in the factories were well aware of their own difficulties in producing quality goods efficiently, it seemed enough that the job was getting done.

Of course, the picture has changed now. A great deal of attention is being focused on manufacturing, particularly the problems of productivity. The changes have come about so rapidly, however, that a good deal of confusion has inevitably occurred. The popular media have propogated many ill-founded myths, many "instant experts" have been quick to seize the limelight, and uninformed politicians have been free in offering their opinions.

One clear message emerges out of all this: the industrial engineering profession is now being offered an opportunity greater than any it has previously experienced. When energy, the environment, or space exploration were in the spotlight, we had only a peripheral role to play. This time our discipline is central, and the others will be seeking a piece of the action. The period of rich opportunity will last a few years at the most; for even though the long term problems will remain, one may be sure that some new crisis will displace the current one in the public eye. Thus we must be both energetic and careful in making the most of this opportunity.

These remarks are intended to serve as a framework for subsequent discussion of issues and priorities for IE research in manufacturing. Some of the obstacles we face will be mentioned first. My general attitude is one of enthusiam, rather than gloom, but we ought to openly confront the difficulties in order to overcome them effectively. Next, some comments on the shifting university/industry/government relationship in research funding will be offered. Finally, one broad area of industrial needs will be examined for its research potential. Although it is only one of several categories which could be discussed, it is one which is particularly rich in opportunities if it is properly understood, and in pitfalls if it is not.

The Obstacles

In meeting the challenges to improve manufacturing productivity and quality, the full range of industrial engineering expertise will be called upon: operations research, human factors, engineering economy, production control, statistics, and all the other things that appear in our academic curricula. Especially important will be the implicit forte of the IE, the ability to synthesize systems out of many diverse technological components. Thus, no major redirection of our efforts will be needed. However, because the demands are great and the IE research community is small, it is essential that we focus our attention on the key problems--ones for which the potential for significant positive impact is high. There are distinct dangers in being distracted by superficial aspects, in getting lost in the forest, in getting spread too thin, and in rushing shoddy work to completion. As one of my friends in industry put it, "we are unaccustomed to swimming downstream."

Under the category of misplaced effort, it seems to me that we should be very careful about studying the problems of productivity, as opposed to doing something about them. It seems to be popular now to conduct surveys of managers' opinions, or to take a trip to Japan and report on what was observed there. It has always seemed ironic to me that someone who professes a concern for productivity would spend his own time in such an unproductive way. There are so many things that could be done that would have a direct and immediate impact that we needn't waste much time looking for something that might work.

Turning to another dangerous distraction, we all know that the field of industrial engineering has an image problem. In most companies, an industrial engineer is someone who performs rather low level, routine tasks, in consultation with a handbook. Our own graduates are quick to discover the mismatch between the education they received and the functions they would perform in the capacity of an industrial engineer in the company they go to work for. Often they conclude, correctly, that it is in their own interest to seek a different title under which to practice the skills they have learned. This is a serious problem for our discipline, but it is one we cannot do very much about in the short term. Images change slowly. In my own opinion, this is one problem that is best ignored. Rather than getting frustrated and hung up about labels, I believe it is better to direct one's energy toward the solution of the technical problems we are best equipped to handle. If we do a good job, the image problem will take care of itself eventually.

We in the universities are accused, perhaps justifiably, of inventing our own imaginary versions of industrial problems. For example, much of the work in the scheduling literature has little to do with the real life scheduling problems encountered everyday in industry. Thus we have to overcome a certain degree of scepticism, even when our intentions to help are sincere. But the problem really goes much deeper. Since about the mid fifties, engineering in universities and in industry have gone their separate ways. To be sure, we in the universities have continued to pay lip service to the notion that our research is ultimately intended to serve industry. And on the other side, companies have claimed to be supportive of our efforts, through token grants and occasional visits. But to be brutally honest, the relationship has been weak in comparison to what existed earlier. If we did not share an interest in the graduates we turn out, there would have been little basis for communication.

Both sides could be blamed for allowing the gap to develop. The federal government also played a role, through the nature of its research funding mechanisms. Historians may be interested in tracing these events, but the important point to be made here is that they took place over a long time. As a consequence, the present generation of leaders on both sides have little direct experience in dealing with the others. The network of personal contacts and relationships is weak across the boundaries. Of course this network is extremely important for information transfer; we know what is happening in other places more often through personal contacts than through formal documentation. They are also important for establishing trust. It is certainly worth a conscious effort to rebuild the network.

A second consequence of the long period of separation is that we really do not understand one another's working environments very well. That is, few academics have spent much time on factory floors, so that they really understand what takes place there; and few industrial managers have any perspective of a university other than that which they had as students. Until this situation is altered, there is little hope that the academic work will seem very pertinent to industry, on the one hand, or that they will be able to appreciate the constraints imposed on us by standards for published work and the university reward system, on the other.

University/Industry Relations

One of the consequences of the recent focus of attention on difficulties in manufacturing is that industry is now very receptive to new arrangements. Purdue University has been very successful in establishing agreements with particular companies to fund a major new research program in Computer Integrated Manufacturing. The dollar amounts are not token (over $1 million per company), and the work to be done is genuine research, not contract development. None of the fears one might have over such an arrangement have been realized. Normal procedures for open publication of research results will be followed, concerns over patent rights and licensing have been worked out, provisions for efficient technology transfer to the sponsoring companies without causing a nuisance to the researchers have been made, and the value systems of both sides have been preserved intact. The organization of this program, which has taken place over the past year and a half, was a thoroughly positive educational experience for me. We do not view other universities as competitors, and would be glad to share our experience.

In our case, the program was initiated without any direct federal support. The NSF has seed money grants to establish centers, with the idea that industry support will eventually take over in planned phases. The use of such a funding mechanism may ease the task of finding company participants, since it hints of getting something for free, but is somewhat less than ideal in terms of guaranteeing real committment. Still, it may be the wisest avenue for some universities to take. The National Science Foundation also encourages individual cooperative research projects through a special funding mechanism. Arrangements of this kind can both spread the money further and enhance your chances of being funded. The real payoff, I believe, is in the relationships established. My own experience, though I was sceptical at first, is that close relationships with industry have improved my research.

Suggested Areas for Research

One of the key problems in manufacturing worldwide is to achieve low unit production cost for items which are produced in small batches. We know how to make items relatively efficiently when they have sufficient volume. In this case, one can afford to invest in special purpose machinery, careful design, analysis of alternative production methods (perhaps even some optimization), and so forth. Generally, one can incur high fixed costs to achieve low marginal costs because the fixed costs are amortized over a large base. On the other hand, if only a small quantity of a particular item are to be produced, the emphasis has to be on controlling the fixed costs, which means using general purpose machinery, a lot of hand labor, and crude methods. One cannot even afford to spend much effort figuring out how to do better. This last point is a particularly important one for industrial engineers to realize. It is worth emphasizing that foregoing analysis is <u>not</u> an irrational choice. When small batch products are viewed in isolation, the lowest unit costs will be achieved in this way.

Of course, from a collective viewpoint, when a shop operates this way continually, batch after batch, it will never achieve high efficiency. Therein lies the critical problem. There <u>is</u> a way out. The basic idea is to aggregate batches to accumulate large product volumes, over which you can amortize the larger fixed costs needed to achieve more efficient production. That sounds deceptively easy--as if only a bookkeeping change were necessary. In fact, however, a great many technical problems stand in the way.

From the standpoint of hardware, the answer lies in flexible manufacturing systems (FMS's), a new breed of systems which has only recently appeared in industry. An FMS is a computer controlled, integrated system of machine tools and material handling devices which is capable of producing a wide variety of product types with little or no set-up delays. The handling of cutting tools and fixtures is automated, so that software changes alone will accommodate the product variation. Of course, these systems are expensive, but the fixed costs are amorti@ed over the entire range of products manufactured. There are many interesting new IE research problems posed by FMS's. Design, resource allocation, and scheduling problems take on somewhat different attributes in this environment, as compared to conventional job shops. Certainly this area is rich in research opportunities.

Even in conventional manufacturing systems, however, there are some excellent opportunities. Remember that the key economic objective is to reduce the fixed cost per batch by sharing investment over many batches. If we were to develop analysis tools which were very cheap and easy to use, every time they were used, and were also broadly applicable to many situations, then the economic barriers to using analysis to achieve more efficient production methods would be lowered. We have tended in the past to emphasize sophisticated (i.e., expensive) analysis tools that require expert attention over relatively long periods of time to achieve savings in marginal costs. Some of our best examples of successful industrial applications involve the construction of very elaborate models. For example, an automobile manufacturer might spend $100,000 figuring out how to save fifty cents per fender. This is entirely appropriate when the product volumes are high, as they are in the automobile industry, but unthinkable in a small job shop. What is needed there is something that might cost a few thousand dollars on a one time basis and only a few tens of dollars per application, including data collection and analysts' time. At the same time, because there would be little benefit from ekeing out small improvements in marginal costs, the requirements for precision are greatly reduced.

Please understand that I do not advocate "quick-and-dirty" ad-hoc procedures which merely automate someone's intuition. The shift in focus on the economic spectrum does not imply a reduction in standards for quality of research. It does imply a shift of attention away from, say, large scale optimization models and toward smaller, aggregate models having proven properties of robustness.

There are, indeed, some very fundamental issues in need of deep research. As an example, consider a job shop in active production. The flow patterns and processing variations are so complex that it is difficult even to know the current status. Even supposing, however, that complete information were instantaneously available, how would one know that the shop is headed for trouble? What information should a supervisor have to avoid making a decision now that will start him down a path to serious difficulties next week? Certainly the simple state variables do not work. A build up in in-process inventory, for example, might indicate an incipient problem, or it might be exactly what is needed to avoid a later problem. Much higher levels of intelligence, perhaps analogous to the positional strategies employed by chess masters, are called for.

There is really no difficulty in finding areas of genuine industrial need, which also offer the chance for academically sound research. My principal concern for the IE profession as a whole is that we may not "get our act together" soon enough to make the most of this rare public outcry for the solutions we can provide. Our background, training, and values--our technical qualifications--are appropriate to the task. What remains to be seen is whether we have the determination and courage to do what ought to be done.

RESEARCH FOCUS IN

PRODUCTION AND DISTRIBUTION

BY

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The problems associating with producing, storing, and distributing products and materials are fundamental to Industrial Engineering. They have also motivated much of the work in Operations Research and more recently in Computer Science. The increasing role of machinery and equipment over the years has caused a shift of primary Industrial Engineering focus from a concentration on work methods and workplace design to a concentration on the design and operation of integrated systems of people and equipment. The advent of computers has dramatically increased the potential for analyzing, measuring, and controlling these systems.

It is interesting to note that very little of the research devoted to production and distribution has been directed toward the understanding or solution of problems actually faced by Industrial Engineers. The research effort has primarily concentrated on developing mathematics for solving (a) general models such as integer programming which, if efficiently solvable, would allow us to better solve many of the production and distribution problems and (b) very limited abstractions of the actual problems, such as the single machine scheduling problems, which could hopefully be generalized to more realistic situations.

Given the recent results relating the complexity of combinatorial problems, one would have to be extremely optimistic or extremely naive to believe that efficient solution methods for general integer programs can be developed or that single machine scheduling results can be extended to realistic problems. One is lead to conclude that neither of the primary areas in which related research has been concentrated seems very promising in terms of developing better approaches for attacking the actual problems in production and distribution.

I believe that we need a fundamental refocusing of our research in production and distribution. This should include: (a) primary concentration on the significant problems actually being faced by Industrial Engineers; (b) a focus on long term contributions rather than near term results; and (c) recognition as a valid research contribution, the development of insight into the problems themselves.

In order to concentrate on the significant problem areas, they must first be identified. The remainder of this paper will be an attempt to at least partially delineate the important problem areas and suggest some general research approaches.

PROBLEM AREAS

The problem areas in production and distribution can be roughly divided into those associated with configuration of the system and those associated with operation of the systems. Generally the operation issues have received more research attention since they are somewhat better defined. However, in terms of impacting the system's performance, the configuration issues are frequently more important. Important research areas related to configuration include information and control structuring, process structuring, product grouping, storage configuration, transportation configuration, equipment selection, capacity planning, and layout. Important research areas related to operation include: aggregation, scheduling, and control.

Information and Control Structuring. It is not unusual to have more man hours involved in gathering, processing, and maintaining information about the system than there is in actually producing and delivering the product. Much of the information is gathered to aid in controlling the system (e.g., to initiate orders, to determine status, to schedule, etc.). While recognizing that many systems are inefficient, we have done little to determine how to structure a good system. An examination of the literature regarding Material Requirements Planning systems gives one an indication of how little we know about designing such systems.

Process Structuring. The decisions regarding how a product is to be assembled is an illustration of problems in this class. The material flow could be along a line or could have a more complex pattern. The possibility exists for storing inventories of parts and work in process. Someone must determine the material flow pattern, whether inventories will be allowed and how much, the operations to be performed at each work station, and a variety of other issues. I am aware of few tools which are of any real help in addressing these kinds of questions.

Product Grouping. Questions regarding product grouping arise in manufacturing, storing, and delivering products. The literature regarding "group technology" is an illustration of the attention which this topic has received in manufacturing. However, most of the literature exalts the virtues of group technology rather than providing tools to aid in the grouping. While it is generally accepted that good product grouping can greatly improve system performance, we know very little about how to do the grouping.

Storage Configuration. Questions regarding how to store things (e.g., parts, dies, etc.) so that they can be efficiently used or retrieved has received some attention from researchers. However, except for a few very simple situations (e.g., single and dual command pallet storage and retrieval systems) there is little to aid one in configuring a storage system. Even these simple situations have only been analyzed under very simplistic assumptions on how the system operates. There are some new research efforts in this area which appear promising, but they address only a very limited portion of the problem in this class.

Transportation Configuration. Again, these problems occur both in moving the products within a facility and in transporting to and from facilities. While there is a vast literature in transportation, only a small portion of it is relevant to the problems in production and distribution. For example, until recently little had been done to assess the advantage of fixed versus variable routes in a delivery system. The considerable literature in routing for the most part addresses only those routing problems with very simple restrictions.

Equipment Solution. The increasing range of equipment available and the need to interface it with other systems' components make these problems extremely difficult. In spite of their obvious importance, I am not aware of any methodology which is of much help in the selection process.

Capacity Planning. This area has generated a reasonable amount of research attention, particularly with regard to plant expansion. An assessment now needs to be made as to whether or not the results of this research can aid us in actually planning capacity expansion. A particular difficulty arises when the expansion requires considerable time but we have little confidence in our preception of the future.

Layout. Problems associated with laying out facilities are a fundamental task of Industrial Engineers. They are difficult both because they are combinatorial in nature and because they are difficult to objectively evaluate. Recent advances in computer graphics have motivated new approaches to attacking the layout problem. However, this research is still in its early stages.

Aggregation. Problems in this area include such questions as whether to produce by order or to aggregate orders and produce in batches, what size runs to make, and how to aggregate products for packing or cutting. While these problems are generally easy to define, their combinatorial nature makes them very difficult to solve.

Scheduling. This is another area where there is a vast literature of which only a small part is of any value in a realistic context. These problems are obviously of great importance since they occur so frequently and in such a wide variety of contexts. What is needed is a fundamentally different approach for addressing these problems.

Control. The control problems are those associated with trying to assure that the system will function as it was envisioned. They include controlling processes, products, quality and costs. Most of the current research questions seem to center around utilizing computers to aid in the control process.

RESEARCH APPROACHES

The first step is a meanful research program in one of these areas is to develop an in-depth characterization and understanding of the important problems which need to be addressed. This characterization should include both the problem structure and the environment in which the problem occurs.

Certain of these problems (probably not very many) will have enough special structure to allow development of efficient optimization procedures. By characterizing such structure we can hopefully develop the optimization methodology required for solution.

Of those problems whose structures indicate that efficient optimization procedures are not possible, some are repetitive and allow only a very short time for solution. Others occur less frequently and allow time for more in-depth analysis. Included among the former are problems such as pallett packing and order-picking. For such problems we should try to develop procedures which are the best possible given the problem setting. The procedures should be based on sound methodological concepts, be empirically good, and when possible have predictable performance measures.

Among the problems where efficient optimization is not possible, but where time and cost permit in-depth analysis, are most of the facility and system design problems. For these problems the concept of "human aided optimization" seems the most promising. This concept involves underlying mathematical models (e.g., optimization, queuing, simulation), a computer graphics interface and a human decision maker. The human guides the process utilizing primarily graphical information and makes the ultimate decisions. The models suggests and help to evaluate alternatives based on input from the human decision maker. The research effort should include developing new models and solution techniques, analyzing the proper role of the human decision maker, and determining graphical interfaces which can provide the human with the necessary insight to guide the process.

SUMMARY

While there is a tremendous potential for research contributions in production and distribution, a fundamental refocusing of effort is needed. Most of the problems are admittedly very difficult both in terms of precise definition and solution. However, this only serves to increase their importance as research topics.

The main focus of the research effort should be on expanding our knowledge and understanding of the problems associated with the processes of designing and operating production and distribution systems and on the development of new methodologies which can be used to improve these processes. This does not mean that we should stop developing new mathematical models and methodology. We simply need to develop the models based on a thorough knowledge of the problems that need to be solved rather than on the basis of what can be solved.

This kind of research will require much longer term commitments and a greater interaction with practitioners who must actually solve the problems. It will also require a greater time commitment before results can be expected. However, I see no alternative if we seriously wish to impact the state-of-the-art in production and distribution.